REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
30 May 97

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
DISPLAYS FOR SPATIAL SITUATION AWARENESS THE USE OF SPATIAL ENHANCEMENTS TO IMPROVE GLOBAL AND LOCAL AWARENESS

5. FUNDING NUMBERS

6. AUTHOR(S)
CLARK EDWIN DAVENPORT

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF ILLINOIS, URBANA-CHAMPAIGN

8. PERFORMING ORGANIZATION REPORT NUMBER
97-050

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
DEPARTMENT OF THE AIR FORCE
AFIT/CI
2950 P STREET
WRIGHT-PATTERSON AFB OH 45433-7765

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

14. SUBJECT TERMS

15. NUMBER OF PAGES
83

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

GRADUATE COLLEGE DEPARTMENTAL FORMAT APPROVAL

THIS IS TO CERTIFY THAT THE FORMAT AND QUALITY OF PRESENTATION OF THE THESIS SUBMITTED BY CLARK EDWIN DAVENPORT AS ONE OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE ARE ACCEPTABLE TO THE DEPARTMENT OF PSYCHOLOGY.

Full Name of Department, Division or Unit

April 29, 1997

Date of Approval

Lori Hendricks

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CM JJ

DISPLAYS FOR SPATIAL SITUATION AWARENESS: THE USE OF SPATIAL ENHANCEMENTS TO IMPROVE GLOBAL AND LOCAL AWARENESS

BY

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THESIS

Submitted in partial fulfillment of the requirements
for the degree of Masters of Science in Psychology
in the Graduate College of the
University of Illinois, Urbana-Champaign, 1997

Urbana, Illinois

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

THE GRADUATE COLLEGE

MAY 1997
(date)

WE HEREBY RECOMMEND THAT THE THESIS BY

CLARK EDWIN DAVENPORT

ENTITLED DISPLAYS FOR SPATIAL SITUATION AWARENESS: THE USE OF SPATIAL ENHANCEMENTS TO IMPROVE GLOBAL AND LOCAL AWARENESS

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF MASTER OF SCIENCE

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O-517

DISPLAYS FOR SPATIAL SITUATION AWARENESS:
THE USE OF SPATIAL ENHANCEMENTS
TO IMPROVE GLOBAL AND LOCAL AWARENESS

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University of Illinois, Urbana-Champaign, 1997
Christopher D. Wickens, Advisor

In order to study the effect of display configuration on the spatial awareness facet of situation awareness (SA), we modified three displays with visual spatial enhancements to study their effects on local awareness and guidance and on global spatial awareness. A 2D coplanar display, a 3D exocentric display, and a 3D immersed/2D plan view display were modified using object display enhancements and visual momentum techniques. Pilots flew each display in a simulated low level tactical environment. Pilots' tasks were to navigate by the most direct route possible between waypoints positioned in 3D space and avoid stationary air and ground hazards (local awareness and guidance tasks). Additionally, they had to detect and verbally locate the position of intruder aircraft relative to ownship (clock position, relative altitude, and distance) that appeared on the screen. They also judged if and where the intruder would cross ownship's flight path (front, behind, not crossing) and the intruder's altitude change (climbing, level, or descending) (the global spatial awareness tasks). Results showed the spatial enhancements were effective in increasing local and global spatial situation awareness but did not eliminate all of the costs associated with each display format. The discussion explores the benefits and remaining costs of each display format in the context spatial situation awareness.

To my wife,

Doreen,

and my children,

Michelle and Nicholas.

For their ceaseless support and love throughout this endeavor.

Acknowledgments

I am indebted to Christopher Wickens who, with infinite patience, insight, and wisdom, shepherded me through this project. I would also like to thank Dr. Nadine Sarter who volunteered to be a reader and whose comments were invaluable not only to the completion of this project, but future ones as well. Also, thanks to Sharon Yeakel for her patience and outstanding programming skills.

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1. Introduction

1.1 Overview

On the night of 20 December, 1995, a Boeing 757 carrying 163 passengers and crew members crashed into the mountains near Cali, Columbia. According to the mishap report (Aeronautica Civil, 1996), a probable cause was "The lack of situational awareness of the flight crew regarding vertical navigation, proximity to terrain, and the relative location of critical radio aids." (3.2.3, page 57). Indeed, in many mishap reports, mostly from the aviation domain, "*situation awareness*" is often cited as causal or as a contributing factor in the mishap.

Mishaps such as the Cali accident are rare because commercial airliners do not normally fly in close proximity to hazards such as the ground or other aircraft. In military aviation, however, tactics often dictate that pilots and crews fly their aircraft close to the ground and to other aircraft as well as hazards unique to the combat environment like hostile weapons systems and defenses.

Crews in both civil aviation and military aviation operate in a highly dynamic, complex systems environment which includes factors in the external environment over which they have little or no influence. The demands on the entire system (which includes the human) are multifaceted and require the crews to attend myriad information sources ranging from their personal physiological-sensory systems to aircraft systems to information sources external to their aircraft.

In a situation where the wrong tasks are off-loaded and pilots/crews select a wrong course of action resulting in a mishap, they are often said to have "lost situation awareness." The ability of human operators to acquire, maintain, and expand their *situation awareness* may give them the upper hand when and if a malfunction or failure of a system component threatens the desired outcome of the process. Unfortunately, the term "situation awareness", while widely used and cited (Human Factors and Ergonomics Special Issue on Situation Awareness, 1995; NATO AGARD, 1996; Holland and Freeman, 1995), may not be wholly understood.

1.2 General Concept of Situation Awareness

1.2.1 State of SA Definition

There is no consensus within the scientific community on what SA is exactly, nor is there a single agreed upon definition. Ideas regarding SA range from a general concept to a construct that can be modeled. On one end of the spectrum, Flach (1995) proposes SA as a concept that does not lend itself to definition but more to a broad idea regarding operator cognition. He argues that in order to adequately study SA, it needs to be bounded. In reference to the growing interest in situation awareness as an explanation for various mishaps, Billings (1995) states "..that it's too neat, too holistic, and too seductive. It is too easy to use it, rather than its *components,* (emphasis added) to explain things."(page 3). On the other end of the spectrum, Endsley (1988, 1995) proposed SA as a construct that can be defined and modeled for study and possible application. In between the two ends of the SA definition spectrum, there are myriad definitions of SA (See Dominguez, 1994). To thoroughly address and discuss the debate regarding SA as a concept or construct is a thesis unto itself. Therefore, for the purpose of this paper, we chose to use Wickens' (1995) definition of situation awareness that addressed both the conceptual and constructural elements to focus on one particular component of SA in the aviation domain, specifically spatial awareness.

Wickens' definition of SA uses a compendium of concepts from Endsley, Billings, Dominquez, Fracker, and Adams, Tenney, and Pew, as well as his own.

> "Situation awareness is the continuous extraction of information about a dynamic system or environment, the integration of this information with previously acquired knowledge to form a coherent mental picture, and the use of that picture in directing further perception of, anticipation of, and attention to future events." (Wickens, 1995)

Wickens indicated that situation awareness is more of an umbrella term encompassing a continuum of interactions between attentional processes and related tasks.

Wickens departs from most of the other definitions in the field by emphasizing that SA is determined in part by the particular relevant situation or task requirement, much like Billings'

(1995) components. In his 1995 paper, Wickens discusses three facets of SA-systems awareness, task awareness, and spatial awareness-as having "...different implications for objective measurement." (Wickens, 1995, pg. 57). However, I will expand the scope of the facets slightly beyond Wickens' discussion.

Systems awareness (Sarter and Woods, 1995) includes awareness of automated systems status, communications, and performance parameters like airspeed, altitude, heading, and other operating parameters. In military systems, weapons status, defensive systems, and life-support systems status are also included. The systems facet of SA could also expand to include the status (fuel, weapons, performance capabilities) of other aircraft in a flight for which the pilot or crew is responsible. An illustrative question is: "What is the status of my/my wingman's systems (fuel, mechanical, communications, weapons, etc.)?"

The second facet is Task Awareness (Funk, 1991). Task awareness relates to planning and executing tasks and procedures in order to achieve mission goals, or "What do I need to do now and what needs to be done, when, in the future?" Task awareness includes not only checklist items or procedural tasks required to change the activity level of aircraft systems, but also involves relating the aircraft's state to a desired state and making appropriate changes. The latter, however, blurs the line between task awareness and systems awareness. For instance, if the desired state of airspeed is 450 knots and the current state is 400 knots, the pilot increases airspeed. Therefore, there is a link between systems awareness and task awareness as there is for task awareness and spatial awareness.

Spatial awareness (Wickens, 1996) is the third facet. Spatial awareness involves the sphere of space surrounding the aircraft that contains threats, hazards, navigation waypoints, and targets and their present and future position relative to ownship's. For instance, threats and hazards are terrain along the flight path, weather, or other types of threats in the military aviation domain. A relevant question is "Where am I in the world and where am I in relation to terrain, the threats, and my target?" Spatial awareness is critical in cases where the task and the systems requirements dictate that the crew flies ownship in close proximity to hazards. For instance, the pilots in the previously mentioned Boeing 757 accident were setting up for an approach for landing and were in mountainous terrain. Unfortunately, because of lack of systems awareness the crew did not recognize faulty information presented to them, and a man-

machine communication failure occurred. The result was that the pilots were unaware of their present position relative to terrain hazards and, consequently, unable to correctly project their aircraft's position relative to hazards. Therefore, their spatial awareness, both globally and locally, was lost.

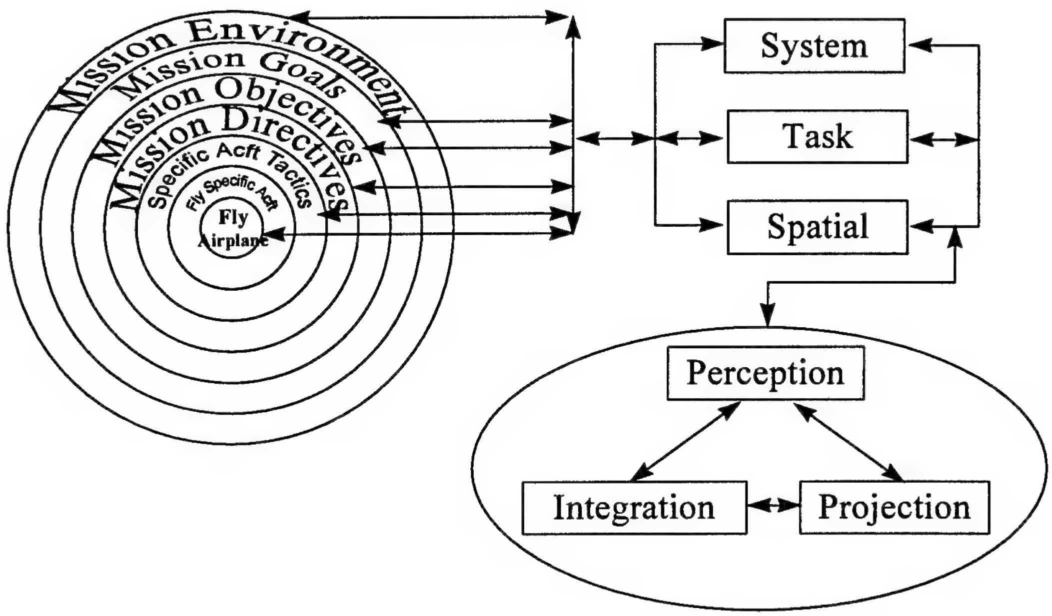
Losing spatial situation awareness tends to have far greater negative consequences relative to the effective and safe completion of a mission. For instance, loss of spatial awareness can, in the worst case, result in unplanned contact with the ground or things attached to the ground or, in a more mundane case, result in getting lost en-route or becoming disoriented. Both the former and latter examples can be just as threatening to mission goals. However, it is important to emphasize that all three facets, systems awareness, task awareness, and spatial awareness, are interwoven and interact, positively and negatively, with one another to affect crews' overall awareness. Therefore, crew members' ability to appropriately attend to each of them and their interactions is critical to successful mission completion.

1.2.2 SA in the Aviation Domain

Operators need a basic knowledge of their field to begin to acquire SA regarding the domain (Endsley, 1995, Adams, Tenney, and Pew, 1995). Aviation is one of the more demanding specialties regarding the amount of *a priori* knowledge practitioners must have. For example, pilots must demonstrate their knowledge and skills to licensing authorities in order to legally fly an aircraft. Therefore, it is assumed that pilots possess a pre-existing model or mental map of "flying" and the basic procedures involved in accomplishing a safe flight, based on the pilot's training and certifications. These "basics" of how to fly an airplane can be considered a kernel, or base model, upon which a mental model is developed and mission specific knowledge is layered. The basic kernel can vary in breadth and depth depending on the particular pilot's experience.

This pre-existing mental model is the precursor upon which Wickens' definition acts. Although pilots' mental models are static knowledge at the beginning of a mission, information acquired as the mission progresses updates their knowledge and revises their mental model. Figure 1.1 illustrates a general concept of layered knowledge in a hypothetical mission specific. For instance, the pilots' or crews' basic mental model contains knowledge required to fly an

Figure 1.1: Hypothetical mission specific mental model showing layered levels of knowledge. The three facets of SA and the perception, interaction, and projection cycle work together within and between the levels of knowledge to update the overall model.



airplane on top of which is layered knowledge about their particular aircraft's performance and capabilities. Depending on the level of training and experience, the latter two levels are considered "basic" in the sense that they function with a high degree of automaticity. Layered on top of the two basic levels of knowledge are higher levels of knowledge that pertain to the specific mission the pilots are flying. Examples of these mission specific layers of knowledge are aircraft specific tactics relative to mission goals; mission directives and rules of engagement regarding the employment of the aircraft and weapons systems in the context of mission goals; the environment in which the mission is executed, including weather, routing, hazards, and threats; and the explicit mission goals themselves.

The mission specific mental model both drives and is updated by a perception, integration, projection or prediction cycle within, and between, the system, task, and spatial awareness facets of SA. As the mission progresses, schema activate proactively in preparation for a pre-planned mission event or reactively in response to an unplanned or unexpected environmental event (Neisser, 1976). The activated schema drives the search for information regarding system, task, and/or spatial awareness. As an example, a crew flies a mission where the primary goal is to perform reconnaissance on a hostile installation and return to home base

(Mission Goal). The mission objectives set to accomplish the goal are to reach the target area undetected (so the crew will have the element of surprise and their chance of engaging hostile forces is minimized), collect the reconnaissance data, and return home. Mission directives relating to the deployment of the crew and their aircraft objectives along with directives regarding specific timing, rules of engagement with hostile, unknown, or friendly forces are known and briefed prior to the mission. Although the mission is flown in a dynamic environment, factors such as weather, terrain, and routing, possible hostile weapons systems and their capabilities, and other factors are briefed extensively prior to the mission so that the crew acquires recent and accurate knowledge that "key" the respective levels of their mental model. Based on this *a priori* knowledge, the crew develops their "mental picture" or mission specific mental model regarding the location of hazards, threats, and their target as well as task and systems "pictures" (Adams, Tenney, and Pew, 1995).

The "mental picture" the crew has formed is critical in setting or priming perceptive and cognitive behaviors (expectancy). The crew knows where the static hazards (terrain) and known threats (stationary defensive systems) are located along their planned route. They are also "primed" for the possibility of dynamic threats, like hostile aircraft or mobile radar sites, and they are more finely attuned to perceive those types of threats (Adams, Tenney, and Pew, 1995). As the mission progresses, schema activate proactively within the crew's model to drive the search for information which is then integrated into the model and used to assess current and future states as they relate to the mission goals and objectives.

Schemata also activate as a reaction to the detection of certain information in order to continuously adapt the model to the new knowledge (Endsley 1995). However, based on the accuracy, breadth, and depth of the crew's mission specific knowledge, the information which the pilots or crews acquire, interpret, and use to update their model may or may not be accurate or beneficial to the end goal of their mission. The pilots' continuous assessment of the world and updating of the model, a perception, integration, and projection cycle characterized by Wickens' definition, is similar to Neisser's (1992) cognitive cycle and Endsley's levels of SA (Endsley, 1988) . A description of the component parts of the cycle follows.

<u>Perception</u>: Perceiving objects (data) in the environment is the first stage of the cycle. Performance at this stage is determined by the degree to which the display and interface design

is matched to human sensory systems and their information gathering techniques. Wickens' identifies this stage as the "...continuous extraction of information about a dynamic system or environment..." It is mostly bottom-up processing but facilitated by top-down processes that drive the search and selection of relevant data.

Integration: This stage is defined as understanding the significance of the information or data retrieved from the environment in relation to the immediate objectives and the overall mission goal. Also, at a lower level, this includes understanding the information or data's significance in relation to other mission parameters and the affect it has on other mission parameters. Integration requires the *a priori* mental model to facilitate the contextual interpretation of the information and, subsequently, add it to the mental model. Because this level, a top-down process, depends heavily upon knowledge and expectations. However, human-machine interface design can, positively or negatively, affect pilots' integration performance. For example, pilots are required to know where in the cockpit and when to look at displays in order to extract data pertaining to a task, mentally integrate the separate pieces into task relevant information, and then, in turn, integrate the information into the mental model. Therefore, previously acquired knowledge in the crew's mental model may influence the interpretation of the new information. Consequently, the subsequent affect on the mental model's update may or may not be accurate. Wickens' SA analogy to the integration stage is "...the integration of this information with previously acquired knowledge to form a coherent picture..." For example, the crew might want to know "How is this new information affecting the mission?" Endsley (1995) notes that it appears that SA often breaks down in the integration stage of the cycle because of the many variables that affect the correct and efficient integration of information.

Projection: The third stage, projection, concerns forecasting future states. Wickens' definition addresses this level with "... and the use of that picture in directing further perception of, anticipation of, and attention to future events." The efficacy of projection is dependent on the validity of the information processed during the first two stages as well as the fidelity of the existing mental model used for the projection. The question answered here is "how is the information acquired going to influence the mission goals and what needs to be done to ameliorate negative or enhance positive affects?" However, if the information gathered in the

perception stage is faulty or incomplete and/or the interpretation of the information in the integration stage is not accurate relative to the real situation, then the crew's forecast using their mental model will not be accurate.

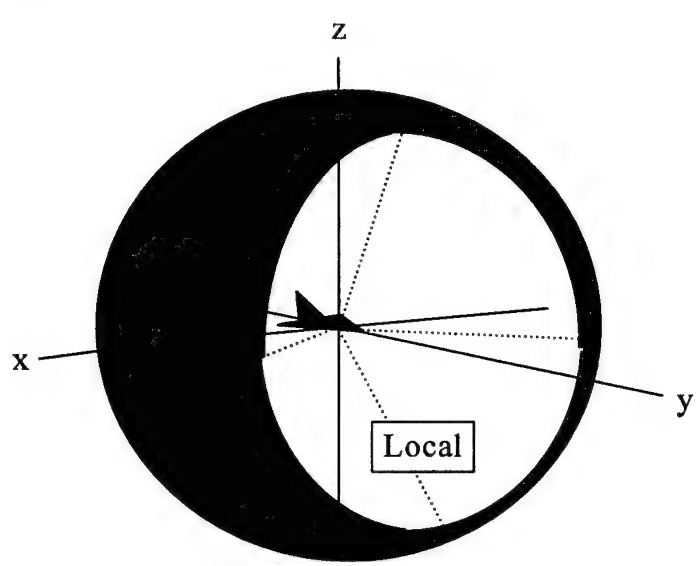
Like Endsley's (1988, 1993) level two and level three SA, Wickens' definition also accounts for the temporal aspect of situation awareness. The need to know what the situation is *now* and how a specific piece of information might affect the mission in the *future* are key elements to an aircrew's ability to update their mental model.

Therefore, the crew's SA depends on the interaction of a range of factors from human-machine interaction through human-human interaction to individual psycho-physiological (physical and mental fatigue, long term reactions to stress, etc.) and physiological interactions (Physiological reactions to environmental demands, mission demands). We will focus here on the human-machine interactions although we are aware that other factors influence the human's assessment of the machine's information.

1.2.3 Spatial Situation Awareness

Spatial awareness can be defined in terms of two features. The first feature, depicted by figure 1.2, is the geographical scope or region, which ranges from local (close, front of ownship) to global (360^0 surrounding ownship), about which pilots must be aware. The second feature is the level of spatial and temporal precision of object location and trajectories within these geographical regions.

Figure 1.2: Global and local spatial awareness regions.



Global Awareness

Global awareness refers to the ability to assess what is occurring within a 360° sphere of variable volume surrounding ownship. The crew needs to know where they are in relation to terrain, weather activity and other threats, and their target destination. Primarily, global awareness relates to *spatial directional judgments* regarding current and projected azimuth, elevation, and distance of a target or hazard relative to ownship (Wickens, 1996). Additionally, global awareness could expand to include the awareness of hazards relative to the crew's target designation. This expanded awareness facilitates the crew's ability to plan ahead, a critical temporal aspect of situation awareness. Therefore, part of global awareness is the affect it has on strategic decision making and planning. Aircrew actions that signal the level of global awareness are either overt, that is, actively pointing out the position of the target, or covert, internally acknowledging a target or event (Wickens, 1996). Global awareness is often characterized by relatively gross, non-precise judgments, e.g., "traffic's at 4:00, its high, and closing." The more refined the judgments and more immediate the need to plan and react, the more awareness moves toward the local awareness end of the continuum.

Local Awareness

Local awareness is considered to be awareness within a section of the sphere in front of ownship that encompasses the anticipated direction of travel. It relates to ownship's immediate attitude (pitch and roll), altitude, and relationships to both desired flight path and near-hazards located to the front, left, and right of the flight path normally within the pilot's forward field of view. However, it could also include objects and events in the immediate temporal vicinity of ownship that, spatially, are not necessarily in front. For instance, if the mission entails a flight of two or more aircraft in formation, local awareness would include not only the pilots' aircraft but that of their wingman or leader's aircraft as well. If pilots make tactical decisions regarding the positioning of their aircraft, they need to be aware of how their decisions will affect their wingmen. In contrast to global awareness, local awareness involves more refined judgments. For example, intercepting a waypoint or target requires more precise judgments in heading, altitude, and airspeed (if target is moving). Local awareness is closely

linked to a local guidance loop activated when the crew senses a need to adjust aircraft parameters.

Local guidance

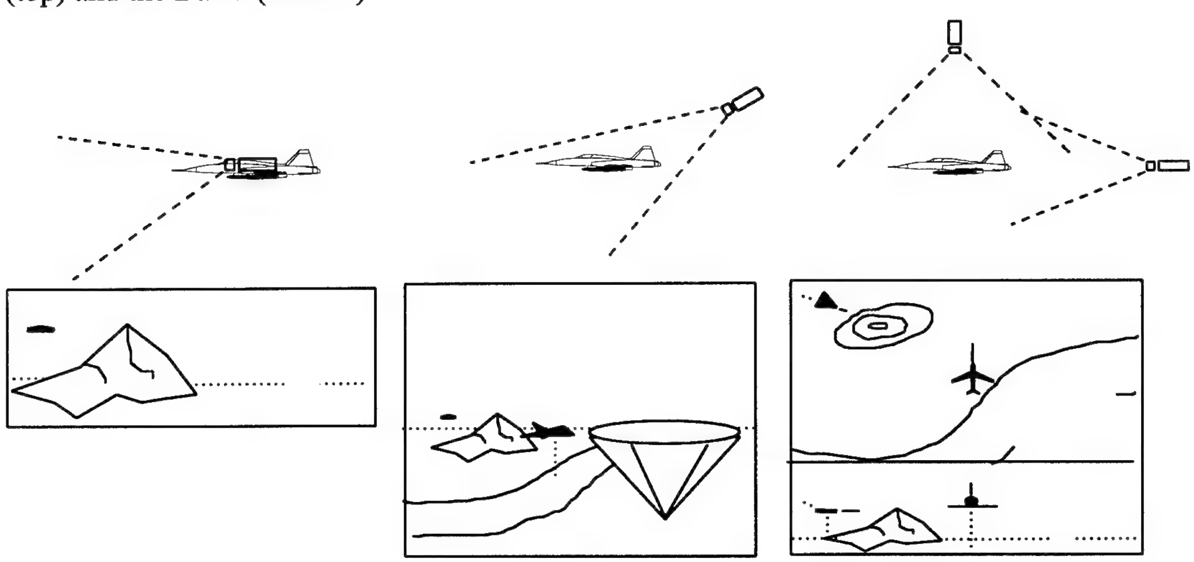
Local guidance is a control loop by which local awareness feeds forward into corrective control action when the pilot wants to fly to a desired path or target or fly from (i.e., avoid) a hazard. It is activated when pilots sense a need to alter their aircraft's flight path or other parameters like airspeed or altitude. If pilots perceive a deviation from desired flight parameters, or the environment dictates a change, they close the guidance loop by initiating control inputs to correct the deviation or make the change. For example, if an obstacle in the flight path requires a change of the path, the pilots' local awareness functions to alert them to the hazard. The local guidance loop is closed when the pilot initiates the maneuver or, conversely, actively decides not to initiate a maneuver. Local awareness and local guidance are coordinated throughout the maneuver until the obstacle is cleared, and the pilot reestablishes the aircraft on the desired flight path.

1.3 Designing Displays for SA

What is the best way to present information to the aircrew that maximizes both their awareness and knowledge of the global environment and also their local awareness and guidance? Additionally, what is the best method of presenting information so the pilot can easily select, process, interpret, and project the displayed information within the time constraints of the particular mission? What display formats benefit the aircrews' own perceptual and cognitive systems during specific tasks? Are displays representing a natural view mimicking an out of the window more advantageous than more schematic displays? Do two-dimensional (2D) displays provide the information effectively or are three-dimensional (3D) representations more beneficial? The literature is extensive regarding the quest for the most beneficial display design for spatial awareness. Many of the findings can be characterized in terms of the different frames of reference to satisfy different task requirements when designing the displays in the studies.

The term "Frame of reference" (FOR) has referred to the orientation of the view with respect to geographical north. Following Aretz (1991), Rate and Wickens (1993) use the terms World Referenced Frame (WRF) and Ego Referenced Frame (ERF) to define the two ends of a continuum. In their treatment, WRF indicated information that was based on a global scale and was displayed via a fixed-map where North was at the top of the presentation. ERF information was more local and displayed via a rotating map where the track of the aircraft was at the top of the display. This reference to orientation has evolved over time to focus more on how much information regarding the world is viewed by the pilot on the display (Wickens, 1997). Figure 1.3 illustrates the FOR continuum. Figure 1.3a illustrates an ERF view, also referred to as an *immersed* view which is analogous to what pilots' see out their forward windscreen. Figures 1.3b and 1.3c show two displays more characteristic of the WRF end of the spectrum where the viewpoint is "outside" of, and positioned so as to show, ownship relative to features and objects in the world. Figure 1.3b illustrates an "exocentric" view that has perspective and depth cues. Figure 1.3c is an example of an exocentric view that orients the viewpoint, or "camera" vertically and horizontally to the aircraft. The result is a co-planar view with the horizontal x and y axes shown in the plan view and the vertical z axis depicted in the planar view. In the

Figure 1.3: Frames of Reference (FOR): Global and Local spatial representation. (a) represents an immersed or "egocentric" view. No global information is presented. (b) illustrates an exocentric view where the camera is "tethered" or positioned at a fixed elevation and azimuth to ownship. The resulting scene gives much greater global information. (c) depicts another type of exocentric view using two scenes to present information on x,y axis (top) and the z axis (bottom).



exocentric views, the camera is pulled back from ownship and oriented in space to provide a view of both ownship and the surrounding world. The degree of exocentricity, also referred to as "tether length", and the dimensionality of the view varies and is discussed later in this paper. The concept of frame of reference parallels the previously discussed continuum of global-local awareness. WRF displays present relatively more global information while ERF displays present relatively more local awareness/guidance information regardless of North or Track up display orientation. Displays vary in their frame of reference by the degree of perspective and other monocular depth cues they employ and the position of the viewpoint.

The degree of perspective used in a display, characterized by the viewpoint angle, coupled with viewpoint location, define the dimensionality of the display. 2D displays use no monocular depth cues to provide information regarding the line of sight axis. 3D displays use monocular depth cues to develop a sense of depth in a display.

Viewpoint location defines the degree of exocentricity in the display. If the viewpoint is positioned to simulate a through-the-windscreen view, then the frame of reference is considered *egocentric* or *immersed.* Several studies have shown egocentric displays have more benefits for supporting local guidance than more exocentric displays (Chudy, 1997; McCormick and Wickens, 1995; Olmos, 1997; Wickens Haskell, and Harte, 1989; Wickens and Prevett, 1995). However, one of the potential drawbacks to immersed displays is the limited amount of global information available due to the restricted forward field of view. The use of a natural or "ecological" geometric field of view (GFOV) in the immersed display presents an undistorted view of the world but results in a "keyhole" effect (Woods, 1984), where the amount of information presented is limited to the forward view and does not provide global spatial awareness information. This effect can be mitigated somewhat by expanding the GFOV.

As we have noted, if the viewpoint is pulled away from the cockpit so that ownship is depicted on the display, the view becomes *exocentric.* The degree to which the display is exocentric depends on the length of the "tether" defining how far the viewpoint is moved from the aircraft. Exocentric displays support global awareness, by definition, more than egocentric displays because more of the airspace surrounding ownship is depicted.

Since the different frames of reference are not defined as discrete states but rather on a continuum defined by viewpoint and the use of perspective cues, they are effectively dependent

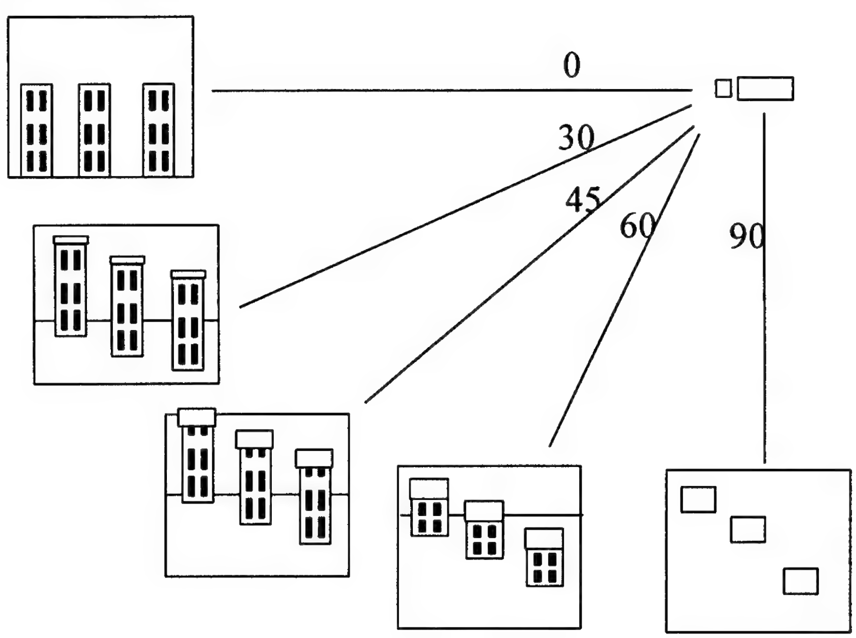
on viewing elevation angle, azimuth angle, and tether length from ownship. Therefore, there is a broad range of display possibilities achievable by varying the viewpoint and perspective, since more of the airspace is depicted.

1.4 2D and 3D Displays

The dimensionality of a display affects task performance. Each format has associated costs and benefits that diminish performance on some tasks and increase performance on others. In this section, each display format is explained along with its accompanying costs and benefits regarding local guidance and both local and global awareness.

If the initial viewpoint is directly over and looking straight down at the focal point of a scene (90° to the horizontal or 90° elevation) and then the elevation angle is decreased to 0°, the views depicted continuously change. As a result, resolutions along the horizontal and vertical axes also change. Figure 1.4 depicts examples of the changing resolutions along the vertical and horizontal axes as the elevation angle is changed (Hickox and Wickens, 1996). As the elevation angle changes between 90° and 0°, the additional use of monocular depth cues provide a sense of perspective and three-dimensionality.

Figure 1.4: Representation of changes in vertical and horizontal resolution as elevation angle changes. (adapted from Hickox and Wickens, 1996)



At the extremes of elevation angle, the resolution along the line-of-sight axis is impoverished which results in what is essentially a two dimensional representation. Alternately, there is good resolution on the orthogonal axis. Therefore, the impoverished depth information parallel to the viewing axis must be displayed in another form, for instance alphanumerically, or through the use of another display. Conventional 2D displays, a radar screen for example, tend to use alphanumeric symbology to present information about the vertical axis to the operator. Since alphanumeric information tends to be harder to use when trying to judge altitude differences and can take longer to process than does spatial information (Ellis, McGreevy, and Hitchcock, 1987; Hart and Loomis, 1980), researchers exploring 2D efficacy have studied the use of other means, like coplanar displays, to present vertical information.

2D co-planar displays (a suite of 2 displays, each depicting axes orthogonal to the other. See figure 1.3c) have the advantage of presenting spatially undistorted information on the axis orthogonal to the viewing axis. The information presented on each display is precise but there is a cost in the need to scan between the two displays (Faye, 1994; Wickens and Haskell,1993; Wickens, Liang, Prevett, and Olmos 1994; Wickens and Prevett, 1995) referred to as *Information Access Cost (IAC)*. IAC may or may not be significant depending on the task for which the display is used. Wickens and colleagues have found that regardless of IAC, 2D display formats are superior to 3D displays in some instances. For example, 2D co-planar displays appear to support focused attention tasks (Rate and Wickens, 1993) or precise estimates of aircraft trajectories (May, Campbell, and Wickens,1996; Merwin and Wickens, 1996) better than 3D displays. Other studies explored baseline characteristics of 3D displays to ascertain why they did not appear to fare as well as 2D displays in certain tasks

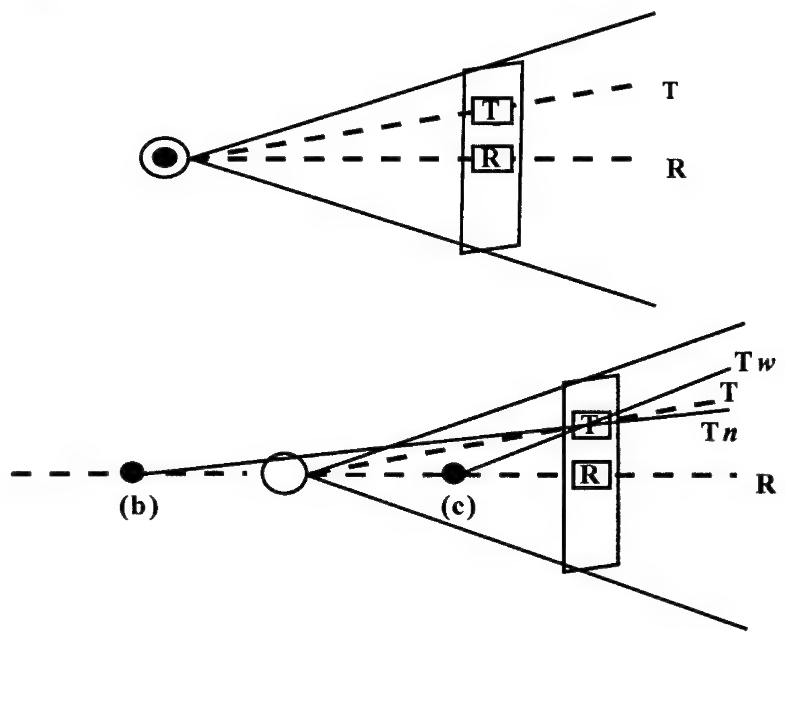
As shown previously, as the viewpoint moves between 0° and 90° elevation, resolution along the horizontal and vertical axes changes. Coupled with the geometric field of view and use of monocular depth cues, a 3D, or perspective, display is presented to the viewer. Unfortunately, there are ambiguities in a 3D display because of the problems of presenting a 3D world on a 2D display (McGreevy and Ellis, 1986). GFOV, elevation angle, azimuth angle, and tether length all interact to enhance the inherent ambiguities in perspective displays. Most

these problems concern foreshortening, or loss of spatial resolution along the line of sight. Each of the contributing factors are discussed below.

1.4.1 GFOV

The GFOV is that amount of the real 3D world presented to the viewer on the view screen and is defined as "the angle depicted by the display image from a hypothetical point where all light rays would converge." (Wickens, Todd, and Seidler, 1989, page56). The point at which all the light rays converge is called the "projection point" or "station point" (McGreevy and Ellis, 1986). Figure 1.5 depicts the interaction between the viewer's position, or viewpoint, relative the view screen and the position of the projection point relative to both the viewpoint and the view screen. The visual angle (VA) is the angle subtended by the viewing screen and depends on viewing screen size and the distance of the viewer, or the view point (VP), from the display. The station point (SP) is the position of the camera or, technically, where all the light rays converge. (Wickens, et. al., 1989). As the station point moves, the GFOV of the scene changes. For instance, figure 1.5(a) illustrates a top down view of the spatial relationship of target (T) to a reference point (R) when the SP and VP are co-located in space. The GFOV then equals the VA of the viewer. Points (b) and (c) represent the spatial relationship between the GFOV and the apparent position of objects in the world and on

Figure 1.5: Viewpoint (a) and station point (b,c) relationship.



the screen. If the SP is positioned a (b), the resulting GFOV is narrower and the target, now referred to as T*n,* appears closer to R. If the SP is positioned at point (c), the resulting GFOV is "wide". Notice that the target, tagged T*w*, appears farther away from R. (Merwin and Wickens, 1996).

The interactions of VA and GFOV in figure 1.5 produce a set of biases that influence the azimuth and elevation judgments made by viewers. Ellis, McGreevy, and others explored this phenomenon and modeled these biases in a set of research projects (Ellis, 1989; Ellis and Grunwald, 1989; Ellis, McGreevy, and Hitchcock, 1987; Ellis, Smith, and Hacisalihzade, 1989; McGreevy and Ellis, 1986; McGreevy, Ratzlaff, and Ellis, 1986). They found that subjects perceived the azimuth of the target relative to the reference point as being closer to an azimuth parallel with the viewing screen than was the true azimuth. Subjects also overestimated elevation angles when the target was above the reference point and underestimated elevation angles when the target was below the reference point. The elevation over-underestimation's were greatest when the target elevation was within $\pm 30^{\circ}$ elevation of the reference point. This bias again reflects a perceptual rotation to an axis parallel to the viewing screen. Overall, they found that a 60° GFOV minimized all the spatial distortions inherent in projecting a 3D image onto a 2D surface.

Other studies, by Barfield, Lin, and Rosenberg (1990), Barfield, Rosenberg, and Furness (1995), and Neale (1995) used dynamic displays and showed that a GFOV of 60° is optimum for making spatial judgments and guidance control inputs. However, there is evidence to suggest other GFOVs support awareness and guidance as well as 60° in a dynamic environment.

Wickens and Prevett (1995) explored the affect of tether lengths on navigation and spatial judgment tasks. They found that a mid-exocentric tether length with 80° of GFOV provided the best support for both tasks. Barfield, Rosenberg, and Furness (1994), in an experiment that examined for target acquisition and tracking found that a 30° GFOV supported the fastest acquisition time and the lowest tracking error.

Overall, it appears that there is no consensus regarding an ideal GFOV. A narrow GFOV to helped local guidance and a wide GFOV helped with global awareness, but not necessarily the ability to locate objects in 3D space. Unfortunately, the distortions caused by wide GFOV's and the lack of global awareness support of narrow GFOV's tends to abrogate

their utility in tasks requiring both local and global tasks. It appears the 60° GFOV used by Ellis and colleagues and Neale is a happy medium for both local and global tasks.

1.4.2 Distance/Tether length

In exocentric displays the viewpoint is positioned away from ownship and the distance or "tether length" affects perception of display detail. Also, if the GFOV is not changed with tether length, the amount of information available in the scene changes. Thus, there is a tradeoff between global and local detail with changes in tether length. A long tether increases the view of the world but decreases resolution of ownship and surrounding detail. Conversely, a short tether increases resolution around ownship yet decreases the global information available to the crew. Wickens and Prevett (1995) examined the affect of tether length on tracking performance on an approach to landing task. They varied the tether length from 0 (an immersed display) to 69,000 feet (far-exocentric) and found that a mid-exocentric viewpoint with a tether of 25,000 feet supported the best global awareness and that the immersed display (tether length = 0) supported local guidance the best. It should be noted that in order to insure the same amount of the world was visible around ownship due to the changes in tether length, Wickens and Prevett adjusted the GFOV for each tether length. This resulted in the immersed display as having a 130° horizontal and 90° vertical GFOV and the far-exocentric display having a 45° horizontal and 30° vertical GFOV.

The tradeoff with increasing or decreasing tether length, without adjusting the GFOV, is the amount of resolution regarding the world around ownship. A tether of medium length appears to allow enough resolution to provide local guidance cues and allow a sufficient amount of the world surrounding ownship to provide adequate global awareness cues.

1.4.3 Elevation Angle

Elevation angle, coupled with GFOV and azimuth angle (discussed later), affects the visual scene. As previously shown in figure 1.4, as viewpoint angle θ changes, resolution along the vertical and horizontal axes changes (Hickox and Wickens, 1996). There is a tradeoff in distance (horizontal) cues and altitude (vertical) cues along the line of sight. The lower the elevation angle, the more the information along the line of sight is compressed causing "foreshortening". The result is confusion between height/altitude (vertical) and distance

(horizontal) information as the elevation angle changes. The elevation angle where there is equal vertical and horizontal resolution is at 45°.

Yeh and Silverstein (1992) examined the affect of elevation angle on altitude judgments in a 3D exocentric display. They varied the elevation angle (15°, 45°, and 90°) and asked subjects to make depth and altitude judgments of an object relative to a reference cube. They found that altitude judgments were harder to make at the 45° elevation while depth (distance) was easier and vice versa for the 15° elevation angle.

Kim, Ellis, Tyler, Hannaford, and Stark (1987), found 45 degrees of elevation in a 3D display provided best tracking in three dimensions. Kim et al (1987) found little difference between performance at angles between 30 and 60 degrees but, again, best performance at 45. Hendrix, Bjorneseth, and Barfield (1994) (as cited in Prevett and Wickens, 1994) supported Kim, et al's findings when they found that judgments of both target elevation and azimuth angles were best with viewpoint elevation angles between 15 and 45 degrees. Wickens and his colleagues used a variety of elevation angles in their exploration of 3D displays in navigation tasks. (Harwood and Wickens, 1989; Olmos, Liang, Prevett, and Wickens, 1994; Wickens, and Prevett 1995; Wickens, Prevett, Liang, and Olmos, 1994). Most of their later studies displays used a 30° elevation angle to increase the relative vertical resolution between ownship and the surrounding world in order to better support vertical spatial awareness.

Although an elevation angle of 45° appears to provide an equal amount of both vertical and horizontal resolution, the most beneficial viewpoint elevation is likely to be dependent on task. The studies discussed above reveal a trend of increasing performance at elevation angles between 45° and 15°, indicating the importance of providing more vertical information.

1.4.4 Azimuth Angle

Combined with elevation angle and GFOV, azimuth angle affects resolution of information along the line of sight. At a given elevation angle, changing the azimuth affects the amount of horizontal information available along the line of sight. As the viewpoint is moved from directly behind ownship toward a setting orthogonal to the line of flight, lateral or "cross-track" resolution suffers. The compression of vertical or horizontal cues adversely affects the accuracy of pilots' tracking in the compressed dimension and their ability to discriminate distance and altitude cues. Ellis, Kim, Tyler, McGreevy, and Stark (1985) varied the azimuth

angle in a 3D display by 45° increments and measured the affects on a tracking task. They reported that there was little change in performance between 45° left or right of 0° behind the reference. They noted that the best performance occurred at 0° and decreased markedly once beyond the 45° boundary. Wickens, Liang, Prevett, and Olmos (1994) studied the affect on vertical and horizontal tracking with azimuth angles set at 0° or 30°. Subjects flew a simulated aircraft down a specified approach path using a joystick. The results of Wickens, et. al.'s study showed negligible difference in the vertical and horizontal tracking between the azimuth angles. However, in this particular experiment, vertical information regarding the aircraft's height above the terrain was color coded to help discriminate altitude deviations. Without this color coding, they note, the vertical tracking error would have been greater at 0° azimuth angle due to the superimposition of the aircraft's predictor symbol with the flight path markings.

Overall, each of the display parameters discussed above affects how a display supports local and global tasks. There is strong evidence from Ellis and colleagues, Neale, and Wickens and colleagues that a GFOV of 50° to 60° is optimum for balancing local and global support. The best tether length, the defining parameter of a display's exocentricity, is strongly dependent on whether or not the task involves local awareness and guidance or global spatial awareness. In exocentric displays, the combination of viewpoint elevation angle and azimuth angle affects navigation performance and global spatial awareness by effecting the amount of vertical and horizontal resolution along the line of sight which creates ambiguity regarding altitude, distance, and azimuth relative to a target. An optimum azimuth/elevation angle combination has yet to be defined in the literature.

1.4.5 Local Guidance and Global Awareness Support

Building on the previous discussion of local awareness/guidance and global spatial awareness, we ask how well these tasks are supported by 2D displays and 3D displays? Recall that local awareness and guidance are not separable tasks but are tightly interwoven and tend to be performed concurrently with each other. Global awareness tasks tend to be less precise than local awareness and guidance tasks and involves more area than what is proximal to the forward flight path.

A review of the literature, much of which was discussed earlier, reveals that 2D coplanar displays tend to support local guidance better than 3D exocentric displays (Merwin

and Wickens, 1996; Rate and Wickens, 1993; Wickens, Liang, Prevett, and Olmos, 1994), although this finding is not universal (Olmos, et al, 1997; Wickens and Prevett, 1995). The factor inferred as to why the 2D coplanar was superior was the cost incurred by the ambiguity in a 3D exocentric display format and the benefit of the precise presentation of information on the horizontal and vertical axes in the coplanar display.

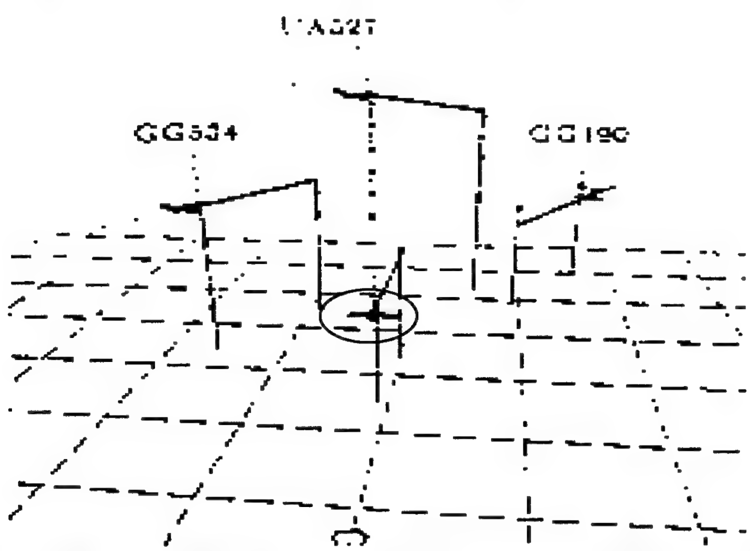
The advantage of a 2D display over a 3D format for local awareness and guidance diminishes or is eliminated when a coplanar display is compared to a 3D immersed display format. Haskell and Wickens (1993) compared a 2D tri-planar display to a 3D immersed display in an approach to landing task. Their results indicated the 3D immersed display was superior to the 2D tri-planar display in local guidance. Haskell and Wickens also assessed the displays' support for intruder detection and position judgments in the forward view (i.e., local awareness). The pilots were presented with either a task that required them to focus attention on one 2D image plane, or integrate across all three axes. Haskell and Wickens reported that the tasks requiring integrated judgments were easier (i.e., interfered less with flight path accuracy) when the 3D display was used to make the judgments. In contrast, the 2D display showed less flight path interference when the focused attention tasks of judging intruder distance was accomplished with that particular display.

In studies in which global awareness was examined, the evidence as to whether a 3D exocentric or 2D coplanar display is superior is mixed (Bemis, Leeds, and Winer, 1988; Ellis, McGreevy, and Hitchcock, 1987; Merwin and Wickens, 1996; Olmos, 1997; Rate and Wickens, 1993; Wickens, Liang, Prevett, and Olmos, 1994). In Wickens' and Prevett's 1995 study, pilots flew predetermined approach paths depicted on a 3D exocentric display with either a long, medium, or short tether, a 3D immersed display, and a 2D coplanar display. The pilots were queried about spatial features of the world in a multiple choice format that required relatively low spatial precision (i.e., Q: What is the next turn on the flightpath like? A: Right >=45°, etc.; Q: where is the runway in relation to you now? A: Right, front, Left, Behind, etc.). The results showed that the 3D immersed display provided the best support for local guidance and the 3D mid-exocentric display (27,000 ft tether) supported global awareness better than the other displays. The 3D immersed display showed the least support for global awareness tasks.

In a study by Bemis, Leeds, and Winer (1988), subjects tracked numerous hostile and friendly aircraft on a simulated USN Combat Information Center using a 2D display or a 3D perspective display. The task was to detect, identify, and tag hostile intruders. The subject had to assign the nearest interceptor to the tagged hostile aircraft as fast and as accurately as possible. Their results indicated that the 3D exocentric display supported greater global spatial awareness accuracy over the 2D planar display with no apparent difference in time.

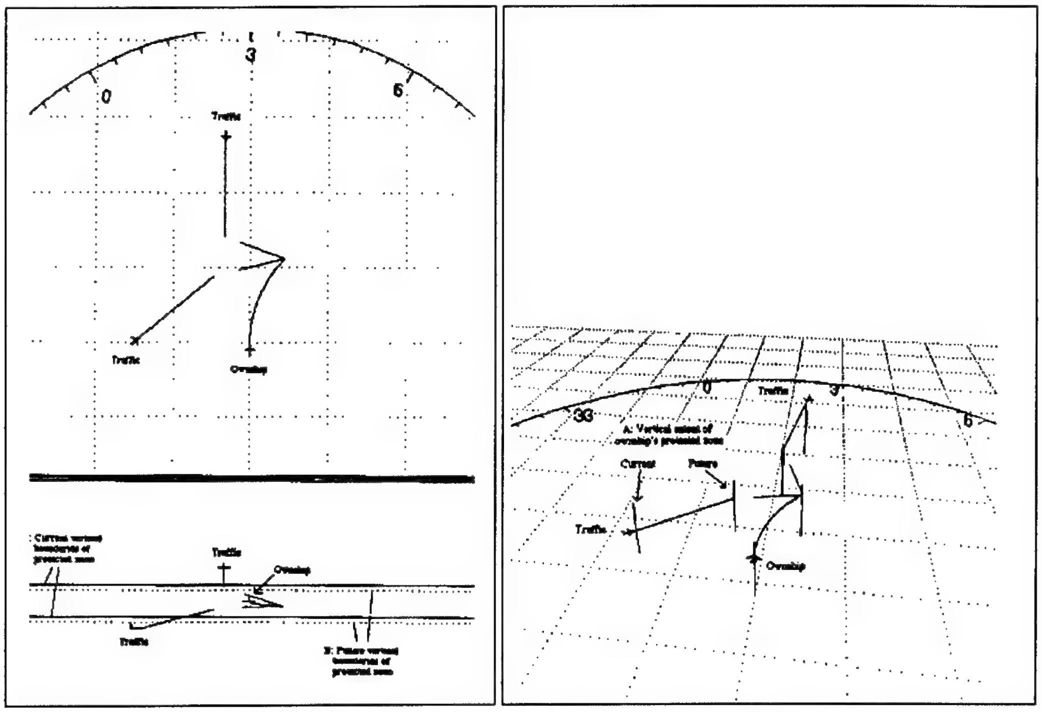
Ellis, McGreevy, and Hitchcock (1987) studied pilots' traffic collision avoidance maneuver selection and decision times using a 2D cockpit display of traffic information (CDTI) and a 3D exocentric CDTI (see figure 1.6). Their results indicated that pilots responded more quickly using the 3D display. Additionally, pilots' selection of an avoidance maneuver was more likely to have a vertical component when they used the 3D display. Ellis, et. al. noted that one reason that the pilots' selected to use the vertical component in their avoidance maneuver was the added resolution of the vertical axis available to them in the 3D display. It should be noted, however, that neither Bemis, et. al. (1988) nor Ellis, et.al. (1987) provided spatial vertical information with their planar 2D displays.

Figure 1.6: Perspective CDTI used by Ellis, McGreevy, and Hitchcock (1987) showing altitude poles. Notice the "x"'s on the intruder altitude poles indicating ownship altitude relative to the intruder. Also, notice flight path predictors.



Merwin and Wickens (1996) compared 2D coplanar and 3D exocentric CDTI displays (see figure 1.7) in a dynamic traffic avoidance task similar to the paradigm used by Ellis, et. al., (1987). The task was a global awareness task in that it required pilots to judge not only the

Figure 1.7: 2D coplanar and 3D exocentric displays used by Merwin and Wickens (1996). Notice the predictor lines.



a b

hazards ahead of their ownship but also the possibility of intrusion of dynamic hazards, in this case other aircraft, from any azimuth and altitude within 360°. Their data revealed that 2D coplanar displays were more accurate in supporting avoidance maneuvers. Whereas Ellis, et. al., found that pilots using a 3D display had a propensity for vertical maneuvers, Merwin and Wickens found that pilots using the 2D coplanar display had a greater propensity to select vertical avoidance maneuvers over those who flew the 3D exocentric display. Furthermore, there were more conflicts registered with the 3D exocentric displays than the 2D coplanar displays suggesting a lack of precision in the 3D display's presentation of information.

The consensus appears to favor immersed displays for local guidance but at a cost for global awareness. There is less consensus about the efficacy of using 3D exocentric displays or 2D exocentric displays for local and/or global spatial situation awareness tasks. It appears each task paradigm dictates the amount of tradeoff between local precision and global awareness that is acceptable to operators and designers.

1.5 Display Format for Combat Tactical Performance: The Olmos Study.

In a study that provides a framework for the current study, Olmos (1997) compared the three FOR's in their support for local guidance, local spatial awareness, and global spatial awareness. Olmos (1997) adopted three display formats used in earlier studies by Wickens and his colleagues which consisted of a 2D co-planar, a 3D exocentric, and a split screen display. The split screen display combined both local awareness and guidance and global awareness displays by presenting a top view which was a 3D egocentric display (immersed view) and a bottom view which was a 3D exocentric display. All exocentric displays were oriented to track up such that ownship's heading was always at the top of the display.

Olmos adopted Ellis and Hacisilhadze's (1990) compass rose arrangement to use as ground reference, rather than using the more common linear grid lines. The compass rose, referred to as a "dartboard", consisted of twelve radials, 30° apart with 1 mile range rings. Ownship's nose was oriented to the 000° or 12:00 radial.

Olmos' tasks and measures required the pilots to fly as directly as possible to, and physically intercept, waypoints positioned in 3D space, a dimensional integration task requiring simultaneous judgments and maneuvering on the horizontal and vertical axes. The pilots were also required to avoid contact with terrain or air hazards. Performance in the navigation task was measured by the amount of time pilots took to intercept waypoints. Additional local guidance and awareness measures were the number of times pilots entered or "contacted" a hazard volume and pilots' detection and avoidance of a pop-up air hazard -- a generic volume -- that was randomly presented along the flight path. Global spatial awareness tasks consisted of detecting and judging the relative spatial location of intruder aircraft that appeared anywhere within the display. Pilots were to detect and then relay, verbally, the intruder's relative azimuth (clock position), altitude (high, level, low), and projected path (closing toward, opening away, or parallel with, ownship).

As predicted, the split screen display provided the overall best support. It supported the strongest in local guidance and awareness tasks due to the incorporation of the immersed 3D display. The split screen display also showed the best support for the detection and avoidance of pop-up air hazard volumes most probably due to the "ecological" nature of the immersed display. However, the split screen display did not support global awareness tasks as well as either the coplanar or the exocentric display. Detection of intruder aircraft took longer with the

split screen display. This was inferred to be due to a combination of two factors. The first was the salience of the top, immersed, display in a complex 3D maneuvering environment which apparently acted to capture the pilots' attention and decreased the amount of scan between the two displays. The second factor was the decreased spatial resolution of the bottom, global exocentric display relative to the stand alone 3D exocentric display which was the only location where global hazards could be viewed by the pilots. The decrease of resolution in the bottom display, in turn, decreased the salience of any new event occurring, and the resolution with which the position and movement of a target could be judged. There was, however, no cost for the split screen suite for the relative position judgments of the intruder.

The difference in performance between the 2D coplanar display and the 3D exocentric display tended to favor the 2D format. The coplanar display supported better navigation as reflected by the navigation times. The exocentric view appeared to cause confusion for the pilots as they tried to intercept the waypoint, as evidenced by the number of waypoints missed for that display (22) when compared with the coplanar display (6). The confusion was a result of the ambiguity present in the exocentric 3D format. Olmos compared the performance of the exocentric and coplanar displays and, after eliminating the data from the those navigation legs on which subjects missed waypoints, found that the benefits of the 2D over the 3D display were eliminated. There were also costs to the exocentric display where lateral maneuvers were required. The azimuth angle of the viewpoint (15° right of ownship's tail (165° right of the ownship heading)) coupled with the elevation angle of 30° probably resulted in compression of visual information regarding lateral flight path navigation. In turn, this lateral compression caused loss of resolution along the lateral axis which may have caused the confusion regarding lateral maneuvers. In contrast, the coplanar display gave an undistorted representation of lateral information on the plan (top) view of the display. Conversely, the exocentric 3D display supported vertical navigation maneuvers better than did the coplanar display, as expected from results of Ellis, McGreevy, and Hitchcock's 1984 work. The cost of the coplanar display in vertical maneuvering could have been a result from the orientation of the bottom, profile, view. Unlike the profile view, illuminating the vertical axis, shown in figure 1.5c, the profile view used by Olmos was such that ownship was oriented so it was traveling left to right in the display. Therefore, objects in front of ownship were depicted to the right in the profile display.

As a result, the pilot may have had to spend time mentally rotating the image to correlate information in the top screen with that on the bottom screen. This may have produced a cost in time and accuracy when coupled with the lack of depth cues in the profile view and the density of information, which could be considered "clutter", on the screen.

1.6 Enhancements to Displays

The previous section illustrated the various strengths and weaknesses of the 2D coplanar, 3D exocentric, and the 3D immersed displays for local guidance, local awareness, and global awareness tasks. These strengths and weakenesses also replicated many of the effects observed in the literature reviewed in section 1.3. Human factors engineering attempts to remediate weaknesses in human-machine interaction by applying principles of human information processing, perception, and cognition in way that can facilitate the development of positive task-display synergies that do not have a cost - benefit tradeoff between tasks. In this section, some of these enhancements are discussed.

In an effort to maximize the benefits of displays and minimize their costs, researchers have searched for methods to capitalize on the perceptual and cognitive capabilities of the human operator. This is particularly evident in studies concerning 3D exocentric displays.

1.6.1 Resolving 3D Ambiguity

Ellis, McGreevey, Hitchcock (1987) used "altitude" posts which were vertical lines connecting aircraft symbols to a base grid in 3D exocentric displays, to disambiguate altitude and distance cues. Figure 1.6, from Ellis, et. al. (1987), also shows the altitude markings on the posts as "x"s. The "x" indicates the altitude of the reference aircraft (circled) relative to each of the respective target aircraft. In the study, which explored the effectiveness of perspective displays in air traffic collision avoidance, the altitude posts helped disambiguate altitude and distance information. Notice in the figure, the straight "predictor" lines extending from the nose of each aircraft. As explained later, predictor displays are important to enhancing display performance.

Ellis and Hacisalihzade (1990) explored the use of symbolic enhancements to 3D exocentric displays to minimize the inherent ambiguity of the format. They superimposed a compass rose over the display's reference grid and studied the effects of varying the angular

divisions in the grid from 15° to 60° sections. Subjects judged the azimuth of a target to a reference point and the results indicated that a compass rose with 30° divisions (relative to clock positions) best supported azimuth judgments. The radials acted to decrease a problem that Ellis and colleagues reported earlier which was the propensity of subjects to judge target azimuth angles closer to standard angles (0°, 90°, 180°, 270°) than was true.

Barfield, Lim, and Rosenberg (1990) manipulated 3D displays using interactive display rotation and shading of objects. They found no benefit of shading objects on judgments of azimuth and elevation. They did find a benefit of allowing subjects to interactively rotate the display on the accuracy of elevation judgments. This makes sense in that by allowing interactive rotation of the display the visual depth cue of motion parallax was produced which allowed subjects to perceive and judge altitude differences with greater accuracy (Wickens, Todd, and Seidler, 1989).

1.6.2 Visual Momentum (VM)

Visual momentum (VM), as described by Woods (1984), refers to the amount of perceptual overlap between two displays that tie them together and, as a result, decrease the cognitive workload incurred when scanning from one display to the other. Related information in the separate displays is perceptually "tied" together through the use of techniques such as color, shape, position, or other visual cues. Visual momentum has been shown to effectively increase orientation of subjects in navigation tasks using separate displays. Aretz (1991) used VM to tie together the two panels of a split screen display which consisted of an immersed view on top of a North-up planar display. He used a wedge on the planar display to define the area of the displayed world that was visible in the immersed display. The results of Aretz's study showed a reduced cost of mental rotation when subjects performed tasks requiring the integration of information between views. Olmos, Liang, and Wickens (1997) obtained similar findings using Artez's wedge as a visual momentum tool. Additionally, they used color to indicate the right and left sides of the display. The data showed the combination of the wedge and color eased working memory load and allowed for quicker response times and more accurate judgments relative to non-enhanced displays. Neale (1995), in work exploring navigation using virtual reality, used VM to help subjects orient themselves and gauge the size

of rooms. His results indicate that the displays with high VM supported more accurate judgments of room size.

1.6.3 Predictor displays:

Predictor displays, depicting where the aircraft will be in x,y,z space, *t* seconds from present, have been found to be extremely strong display enhancements (Wickens, Haskell, and Harte, 1989). Jensen (1981) compared different levels of prediction in an approach to landing paradigm. Pilots flew a curved landing approach to a runway in a simulator using a heads-down immersed display format. Jensen manipulated the amount of prediction combined with the amount of "quickening" ("...the immediate presentation of the anticipated results of the controller's actions." Jensen, 1981; page 356). He found that for lateral control, the greater the degree of prediction used, the better the performance. As mentioned briefly in the beginning of this section, Ellis, McGreevy, and Hitchcock (1987), in a study examining cockpit displays for traffic information (CDTI) (See figure 1.6), used predictor lines to indicate future position of ownship *and* other aircraft. Merwin and Wickens (1996) also used predictors depicted in figure 1.7a and 1.7b, in both 2D coplanar and 3D exocentric displays in a more elaborate examination of CDTIs and their role in air traffic collision avoidance. In both Ellis, et. al. (1987) and Merwin and Wickens (1996) the predictor displays were critical to the task of pilots' forecasting the position of their ownship relative to intruders and judging whether or not a conflict would occur.

1.6.4 Attention Guidance

Alerting cues can be incorporated into display designs to draw the operator's attention to a particular event or events. This is particularly important in displays where there is a highly salient component that effectively captures and holds pilots' attention. This phenomenon was demonstrated by the immersed view display panel in the split screen display suite used by Olmos (1997) where events that occurred in the bottom, global view display, were often undetected. The lack of perception of an event due to the salience of another part of a display or the cognitive demands of another task can be decreased using visual or auditory cues.

Auditory cues have traditionally been used in the cockpit as alerting systems to indicate to the crew that a system has malfunctioned or is not correctly set. The auditory cues, in the

forms of buzzers, bells, tones, or in the case of more modern ground proximity warning systems, synthesized voice warnings, are designed so that they are salient in a high task environment. Other auditory cues that are designed for less critical events are less salient and may not be perceived. The effectiveness of auditory cues in an event alerting paradigm is discussed in the section below regarding a study by Chudy (1997). Visual cues, if designed correctly and incorporated into the display should also effectively enhance operator performance.

As a visual attention guidance cue, the use of flashing in combination with color or contrast has been found to be effective. Flashing is similar to motion cues due to its dynamic nature (Van Orden, Divita, and Shim, 1993). Treisman (1986) grouped movement along with color, size, orientation, and depth as characteristics that the visual system extracts and processes early. She noted that the early processing of these characteristics leads to easy search and detection when they are present. Thackray and Touchstone (1991) studied the effect of flashing at 4 Hz on intruder detection in an Air Traffic Control paradigm. Their results indicated that flashing used as a redundant cue to shape was superior to color in attracting attention. Van Orden, Divita, and Shim (1993) explored flashing and luminance as redundant codes to shape and color. Their results indicate that using flashing (at 3 Hz) lead to faster response times than did luminance when coded redundantly with shape and color.

1.6.5 Application of Cognitive Engineering Enhancements: The Chudy Study

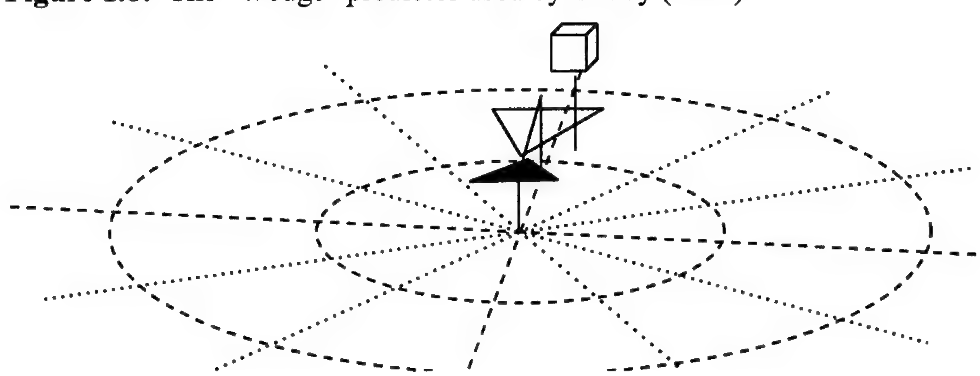
Chudy (1997) modified Olmos' displays in an effort to explore the effects that certain enhancements had on local awareness and guidance as well as global spatial awareness. Accordingly, Chudy retained Olmos' tasks and measures for comparison purposes. He addressed the weaknesses of the displays used by Olmos and enhanced them, in part, by following the Proximity Compatibility Principle which states that "Displays relevant to a common task or mental operation (close task or mental proximity) should be rendered close together in perceptual space (close display proximity)" (Wickens and Carswell, 1995, page 473). Chudy employed visual momentum, color, auditory cues, and predictor displays to enhance the task-display interface.

To address a possible cost of mental rotation incurred by the "left-to-right" orientation of the profile view in the coplanar display, Chudy reoriented the bottom profile display to a rear

tethered view. The viewpoint, instead of positioned 90° to the right of the flight path, was positioned directly behind the aircraft. Repositioning the viewpoint directly aft of ownship provided a more natural mapping between the top and bottom displays in the coplanar display suite which ostensibly removed the need for the pilot to mentally rotate the image to find corresponding features between the plan and profile views. Chudy enhanced transition between the two displays by using color to provide VM. He color coded terrain according to its altitude above the ground in both displays which created visual momentum between the displays to help the pilots orient themselves when they scanned from the planar view to the profile view.

Chudy addressed the weakness of the 3D exocentric display for lateral navigation by changing the azimuth angle offset of the viewpoint from the 15° value used by Olmos, to 8° right of ownship's tail, in order to increase lateral cross-track resolution. To address the 3D ambiguity of distance representation between ownship and hazards in the forward flight path, he also added a predictor "wedge" to the front of ownship as illustrated in figure 1.8. The apex of the wedge was attached to the nose of ownship and extended 1.5 miles in front of and 0.5 miles either side of the flightpath at the front. If the wedge entered a hazard volume it turned from white to red. This was designed to cue the pilots as to their lateral and vertical clearance from hazards. To counter the missed waypoints that resulted from the altitude/distance ambiguity found in the exocentric display, Chudy altered the waypoints so that they changed shape to command a climb or descent if the pilots were too low or high respectively, to intercept the waypoint. Recall that the results of Olmos' study showed that the exocentric display had poorest support for judging altitude of intruders. In order to improve the display's performance, Chudy used color to code the intruder's relative altitude; red for low, black for level, and white for high.

Figure 1.8: The "Wedge" predictor used by Chudy (1997)



To address the long latency of pilots' response to the global awareness task of intruder detection in the split-screen display which had resulted from inappropriate attention allocation to the immersed display, Chudy added an auditory cue in the form of a short tone when a pop-up or intruder appeared. The cue was added to all three displays but was specifically designed to support performance for the split screen display. He also shortened the tether in the 3D exocentric view of the split screen display to 25,000 feet in order to increase the resolution of the display. Further, he widened the GFOV of the top display to 60° based on previous findings by McGreevy, Ellis and colleagues (McGreevy and Ellis, 1986; Ellis, Tharp, Grunwald, and Smith, 1991; Ellis, and Tyler, 1985(as cited in Barfield Rosenberg, and Furness, 1995)), Barfield and colleagues (Barfield, Lim, and Rosenberg, 1990; Barfield, Rosenberg, and Furness, 1995), and Neale (1995) who worked with desktop virtual reality navigation.

The results of Chudy's enhancements were most evident in the local guidance and awareness tasks measures of navigation time and contacts with hazards and response times to pop-up targets. The 3D exocentric display used by Chudy showed a marked improvement over Olmos' 3D exocentric display in with the number of missed waypoints which fell to around the same number as the other display formats. Navigation times for Chudy's exocentric display also improved and were equal to the other two displays. The addition of the VM enhancements to the 2D display appeared not to have had a great impact on navigation time but was considered a factor responsible for the decrease in the number of hazard contacts. The number of contacts dropped from 41 in Olmos' coplanar display to 4 in Chudy's display. The reorientation of the profile display in the 2D coplanar suite, coupled with the orienting cues provided by color coding terrain height, improved the suite's support for local guidance and awareness tasks.

1.7 Purpose of current study*:*

The purpose of the current study is to explore the efficacy of further graphical enhancements to head down displays in order to improve their support for spatial judgments, and provide a more detailed examination of spatial awareness using a similar task paradigm used by Olmos (1997) and Chudy (1997). We examined each display format and developed graphical enhancements for each of them to assess the improvement of their overall effectiveness for the spatial awareness facet of situation awareness.

1.7.1 Enhancements to Displays

Three displays were developed on the basis of Olmos' and Chudy's work described previously. In addition to enhancing individual displays, changes were made that were common to all three displays. All three displays retained the "dartboard" or "compass rose" ground reference arrangement used by the two previous studies and by Ellis and Hacisalihzade (1990). The other enhancements adopted across all the displays were of a more symbolic nature and are reflected in current, operational displays. They are the use of color redundantly coded with shape for Identification of Friend or Foe (IFF) of intruder aircraft. As an attention cue, the intruder symbols were flashing. These enhancements were chosen in order to provide more salient visual cues regarding the intruder's appearance and presence in the displays. Both Olmos (1997) and Chudy (1997) used a red, aircraft shaped, non-flashing symbol to the intruder. The results of Olmos' experiment showed that the split-screen display did not support intruder detection very well due the perceptual salience of the immersed display. Chudy ameliorated the problem with an auditory cue while we chose to use visual cues as discussed below.

The use of color and shape to redundantly code information has been widely shown to decrease search time and increase accuracy (Christ, 1975; Jacobsen, Neri, and Rodgers, 1985; Jacobsen, Rodgers, and Neri, 1986; Kopala, 1979). In the current study, however, we do not use color and shape to aid in search. We use it to identify an object in the display. In an identification task, the category of the object is not known until it appears (Luder and Barber, 1984). Pilots must both detect the appearance of and categorize the object. A review of the literature reveals that color and shape are processed differently (Luder and Barber, 1984). Color appears to be processed in parallel as evidenced by a lack of significant increase in response times to detect uniquely colored objects as display size increases (Carter, 1979; Noble and Sanders, 1980 and Smith, 1962(as cited in Luder and Barber, 1984)). Although we did not present more than one intruder at a time, the combination of the display's colors and the number of hazard volumes could be considered "clutter" which might effectively act to increase display size. Therefore, color-shape redundancy was used to increase the discriminability of the intruder. We used the following color-shape coding in all three displays for intruder identification; red triangles for "enemy", blue circles for "unknown", and white squares for

"friend". To further enhance detection of intruders we used flashing of any intruder as a means to attract pilots attention.

Flashing was selected as an attention cue to alert pilots to an intruder on the screen. We chose to use flashing rather than an auditory cue as an alerting cue because there are myriad of auditory cues now used in the operational cockpit ranging from voice communications to weapons status cues to warning signals of various sorts, and the addition of another auditory cue might decrease its salience given the number of auditory signals already present in the cockpit. Furthermore, unlike an auditory cue, flashing of the intruder intrinsically draws attention to the intruder's location in the display.

1.7.2 Object display enhancements to improve SA judgments in the 3D exocentric display.

As mentioned previously, the ambiguity inherent to 3D exocentric displays regarding target or hazard location is an impediment to their effectiveness in supporting global spatial awareness. Recall that Olmos reported low support of the exocentric display for vertical judgments of intruder aircraft. He did not incorporate specific enhancements to the display, so the low support was expected. Chudy used color to code relative altitude in order to ameliorate the ambiguity in his modification of Olmos' exocentric display. This was effective, but because color coding is not inherently a spatial cue, we did not think color as an altitude cue satisfied our requirements regarding spatial enhancements to the exocentric display. Also, since color is used in existing color tactical displays to denote friend or foe status (IFF), pilots might carry biases toward the meanings applied to color (e.g. Red = Danger or Stop, Green = Safe or Go) and problems from confusion regarding the meaning of the color could arise. Therefore, we selected spatial enhancements in the form of object display elements based on a large body of work which has suggested that object displays can facilitate certain kinds of task performance (Barnett and Wickens, 1984; Bennett and Flach, 1992; Bennett, Toms, and Woods, 1993; Buttegieg and Sanderson, 1991; Sanderson, Flach, Buttigieg, and Casey, 1989; Wickens and Carswell, 1995). Below, we review some of the research that has addressed the efficacy of object displays for spatial judgments.

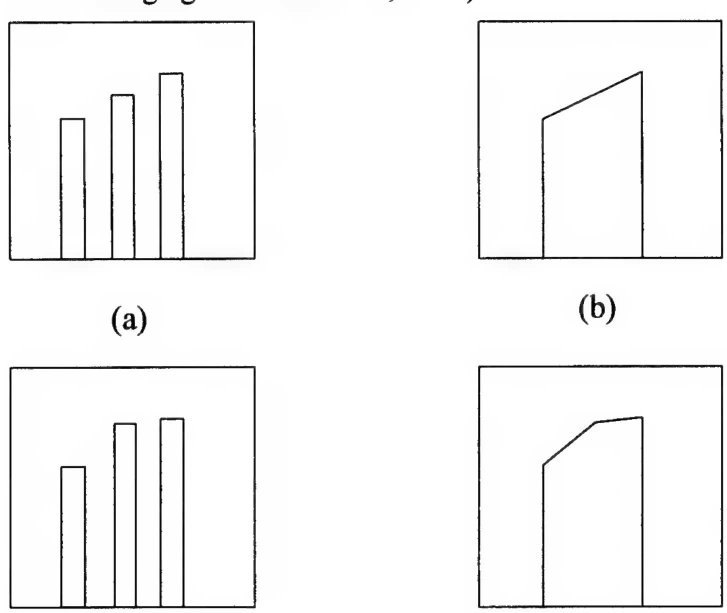
Object displays are assumed to serve two functions. First, according to Treisman (1986) objectness is one of the characteristics of a stimulus that the visual system processes early.

Therefore, objects support direct perception of shape. Additionally, in the object file theory (Kahneman and Treisman, 1984), it is asserted that when the whole of an object is attended to, all the component parts of the object are also available for selection.

Emergent features are described by Bennett and Flach (1989) as "The additional properties that arise from the interaction among configural stimulus conditions" (pg. 517). Pomerantz and colleagues (Pomerantz, 1986; Pomerantz and Garner, 1973(as cited in Bennett and Flach 1989); Pomerantz and Pristach, 1989) laid the foundation for the use of emergent features in displays with their work on configurality, in an experiment involving identifying the orientation of a pair of parentheses [i.e., () vs. ((]. The authors found that classification speed was increased when the parentheses were configured such that they formed an emergent feature [e.g., the closed parenthesis pair ()]. Pomerantz and colleagues' work as well as work by Bennett and Flach (1992) show that emergent features do not have to come from objects, and their effectiveness is not automatic but is dependent on the mapping of task variables to the display.

Figure 1.9 shows two types of configural displays (displays where mapping of the data variables result in an emergent feature). The bar graph in figure 1.9(a) illustrates an example

Figure 1.9: Emergent features in (a) non-object and (b) object displays. Notice the difference in the salience of the "out of normal" conditions in the bottom displays. (Adapted from Buttigieg and Sanderson, 1991)



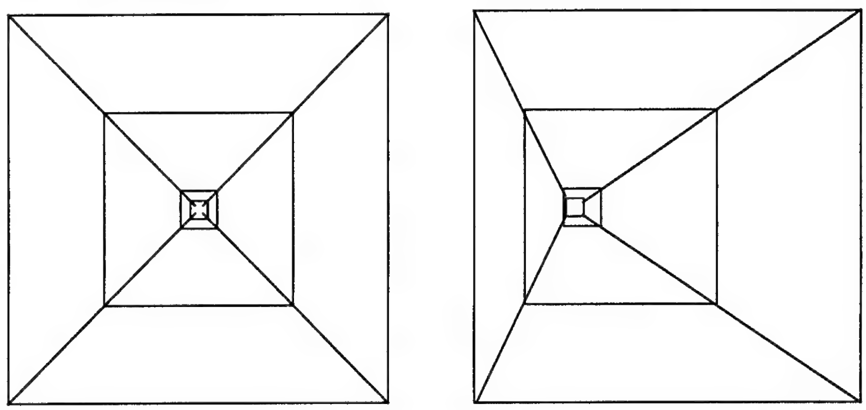
where the emergent feature is inferred by the operator through the apparent linearity across the tops of the bars. This type of *implicit* emergent feature is used in certain system controls where each data variable is coded such that in normal conditions the tops of the bars are aligned horizontally. The observer must infer linearity since there is no visually explicit connection between the bars. An example is a C-141 transport aircraft where the engine indicators are mapped so that when the engines are running normally, the "tape" or bar for each indicator is aligned with the ones arrayed beside it. Any deviation from the linearity alerts the crew who can then troubleshoot the problem. Figure 1.9(b) is an example of an object display. In this example, the data points between the bar graphs were connected with a horizontal line. The "closure" results in an object with a specific geometry and symmetry. When data are properly mapped, the resulting object's emergent feature is visually *explicit* and is predicted to lead to direct perception of the object.

Results of work by Buttigieg and Sanderson (1991), in a complex systems monitoring and fault detection paradigm, show that the effective mapping of data variables to an object display, so that the resultant emergent feature satisfies the meaning of the task, leads to performance indicative of direct perception. Their results indicated that an object display with mis-mapped data variables performed well below the performance of an object where the variables were mapped to accurately reflect the task. Wickens and Carswell (1995) discuss the use of emergent features inherent in object displays in the context of the Proximity Compatibility Principle. They argue that direct perception of emergent features replaces the cognitive workload of computing information with the overall desired result being to reduce the load on working memory.

Most of the previous work described involved the use of object displays in monitoring of, and fault detection in, complex process control systems. Some work involved the use object display elements in local awareness and guidance paradigms involving flight path navigation (Wickens and Andre, 1984; Wickens, Haskell, and Harte, 1991; Theunissen (1994)). For example, Theunissen (1994) exploited the use of squares as objects to produce a "tunnel-in-the-sky" visual flight path guidance display illustrated in figure 1.10. By connecting a series of concentrically smaller squares with lines connecting their corners, Theunissen created the illusion of a path. When the pilot was on centerline and on the correct glidepath, the vanishing

point was in the middle of the screen. The emergent feature was the symmetry of the boxes nested within one another. If the pilot was off course, laterally or vertically, the result was in a highly salient visual asymmetry in the path. Other than the work noted above there is a scarcity of work regarding the use of object displays as tools for global spatial awareness.

Figure 1.10: Examples of Theunissen's tunnel in the sky display. Figure (a) depicts the display when the pilot is on course and glide path, figure (b) illustrates the display if the pilot is left of course and on glide path.



a b

Figure 1.11 is a picture of the 3D exocentric display used in the present study. The task of judging the relative altitude of intruders in the exocentric display is complicated by the spatial ambiguity of the display. Analysis of the relative altitude judgment task revealed that, in the context of the Proximity Compatibility Principle, it is a *computational integration task* (Wickens and Carswell, 1995) which requires the pilots to compare the altitude posts of ownship and intruder and judge which is higher. Therefore, the relative altitude task should lend itself to the use of object displays to spatially integrate the altitude information. Figure 1.12 shows the evolution of object display element enhancements to the exocentric display. Figure 1.12 (a) represents an unenhanced presentation of ownship and intruder altitudes used by Olmos (1996). Notice the difficulty in visually judging relative altitude. Figure 1.12(b) illustrates the addition of an air vector between the two aircraft symbols. The resulting figure does not necessarily disambiguate the altitude differences even though they are connected. Cleveland and McGill (cited in Wickens, 1992) noted that judging the length of lines with non-aligned baselines is difficult. Figure 1.12(c) shows the effect of adding both a ground and air vector between the two aircraft. The ground vector, overlaid on a flat surface, connects the two

Figure 1.11: Screen shot of 3D exocentric display

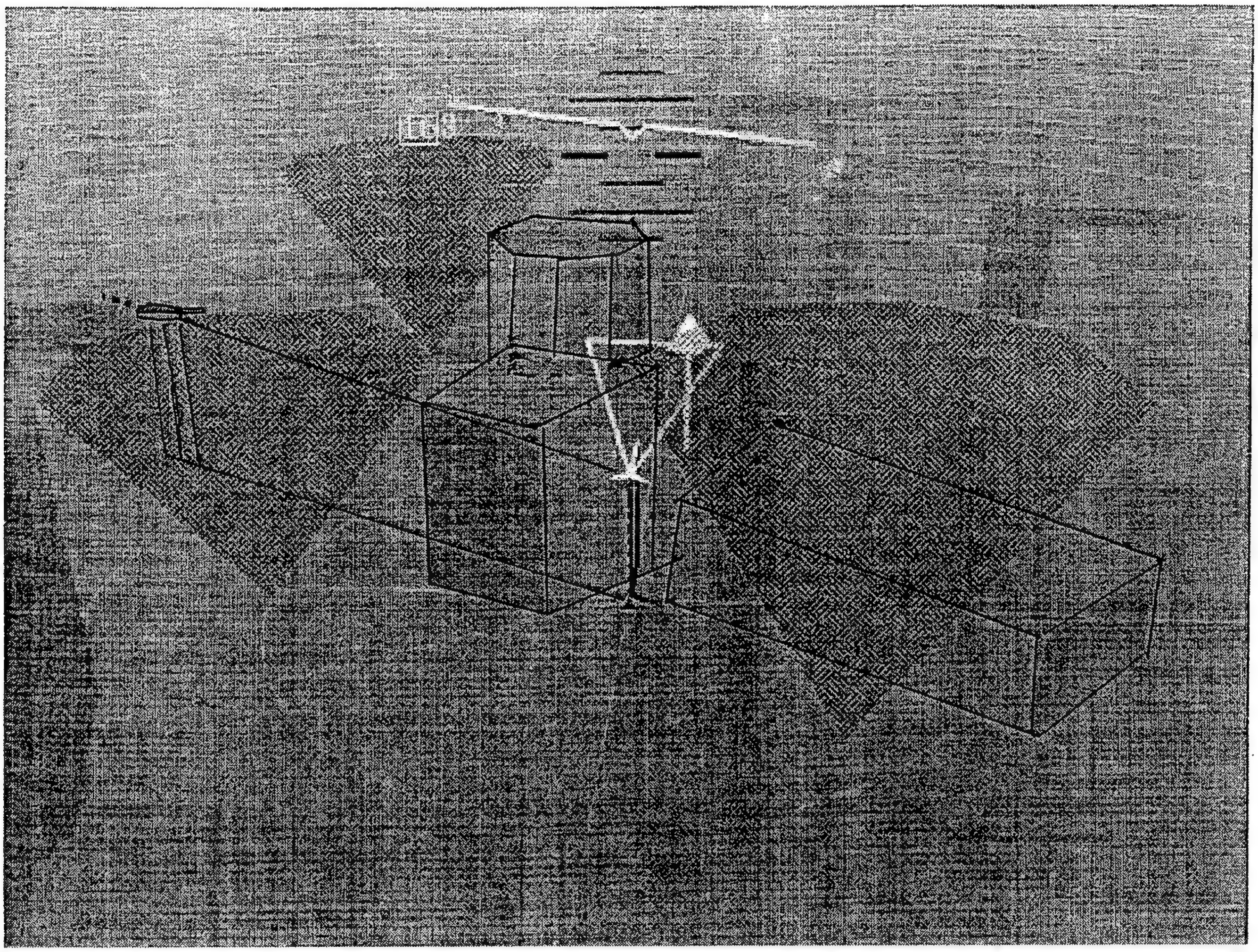
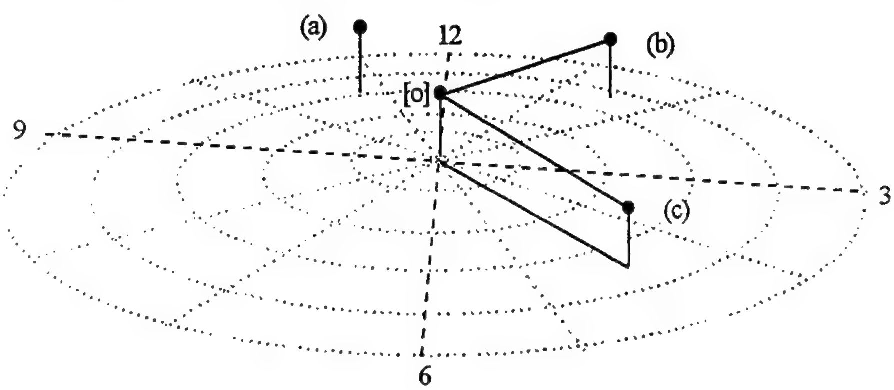


Figure 1.12: Evolution of object display elements in a 3D exocentric display. (a). Judging the relative altitude of a target to ownship (o) using only a vertical height (altitude vector) is difficult because of the display's inherent ambiguity. (b) illustrates t the effect of adding a horizontal air vector between ownship and the target. The relative altitude is still not apparent. (c) shows the effect of making an object by using a horizontal ground vector to close the figure. The resultant shape should make the judgment of relative altitude more accurate and timely than unenhanced 3D exocentric displays.



ground points and closes the figure to create an object. The air vector acts to "close" the figure and create and object. The resulting parallelity of the object spatially presents the relative altitude differences to the pilot. If the air vector slopes down from ownship, the intruder is at a lower altitude. Conversely, if the air vector slopes up from ownship, the intruder is higher. The explicit emergent feature of convergence or parallelity, in this instance, provides the pilots with a geometric, spatial representation of altitude difference which replaces their need to compute the relative difference in the altitude vectors of each aircraft.

The previous discussion has shown how object displays will support integrative tasks of comparing ownship-intruder altitudes. An added benefit that is predicted from the use of object display elements in this display is an increase in accuracy and decrease in response time for azimuth and distance judgments. Both of these tasks are focused attention tasks in that they address a single feature of the object. In this case, however, they both are represented by a single data point, the location of ground point of the intruder's altitude vector. We predict that the ground vector will benefit these two judgments by acting as a pointer. In conjunction with the compass rose ground reference overlay, the ground vector will act as a clock hand to disambiguate azimuth judgments by precisely delineating the current azimuth. The terminus of the ground vector with the intruder's altitude vector should act as a salient pointer for the distance judgment. This benefit is predicted by Kahneman and Treisman's (1984) object file theory which asserts that all of the component parts of an object are available for perception if desired. Pomerantz and Pristach (1989) note that "...Subjects may prefer to attend to more salient emergent features than to less salient lined segments but this is not any sort of failure...." (p642). Also, Bennett and Flach (1992) contend that a single geometric display can support both divided and focused attention tasks if the object display is considered composed of hierarchical features of varying salience to the task. In the case of the object shown in figure 1.9(c), the whole object defined by its shape and parallelity is used for the integrative task of judging relative altitude, and its component parts, the terminus of the altitude post and ground vector, is used to determine azimuth and distance.

The remaining two global spatial awareness judgments, projection of intruder-ownship flight path intersection and the intruder's vertical status (climbing, level, descending), involve a time and motion element. The use of the object display elements is predicted to

support these judgments through the change of the object's shape over time. For example, if the intruder's forward vector led to a crossing of flight paths in front of ownship and its vertical vector was decreasing , the resultant change in the object's shape and its movement across the ground would allow pilots to directly perceive the trend. Overall, we predict that the addition of object display elements to the exocentric display will improve the accuracy and response times for global spatial awareness tasks.

In the current study we used a parallelogram to provide emergent features that would help resolve ambiguity of relative altitude judgments in spatial form. The data variable mapping is straightforward since there are only two variables being mapped; altitude of ownship and altitude of the intruder.

1.7.3 Display Enhancements to Improve SA judgments in the Split Screen Display

The split screen display used by Olmos (1997) and by Chudy (1997) consisted of a top immersed 3D view with 60° GFOV for local guidance and awareness, positioned over an exocentric display which was designed to provide global awareness. Analysis of the data with the split screen display indicated good support for local awareness and guidance but poor support for global spatial SA because of the high salience of the top immersed display and the ambiguity of the bottom, exocentric, display. Therefore, we looked for enhancements to improve the support of the display for global SA in the hopes we could provide the basis for good local and global awareness in a single display suite. Keeping the focus of our enhancements on the spatial aspects of the display, we modified the bottom, global view from a 3D exocentric view to a planar, top-down view since this was the panel designed to provide global SA. A planar display provides pure information on the horizontal axis which can be represented on a smaller display. Recall that one of the problems with Olmos' display was the number of contacts with hazards in each display (41 for the split screen specifically). We inferred, from watching pilots fly with the display, that most contacts in the split screen display were a result of misjudging the horizontal passage over a hazard. In other words, the immersed display did not provide adequate information to the pilots regarding when the hazard over which they were flying was sufficiently behind ownship so that they could descend without contacting the hazard. Therefore, pilots using the split screen display tended to descend into the hazard over which they were flying. We predicted that the use of a top-down display for global

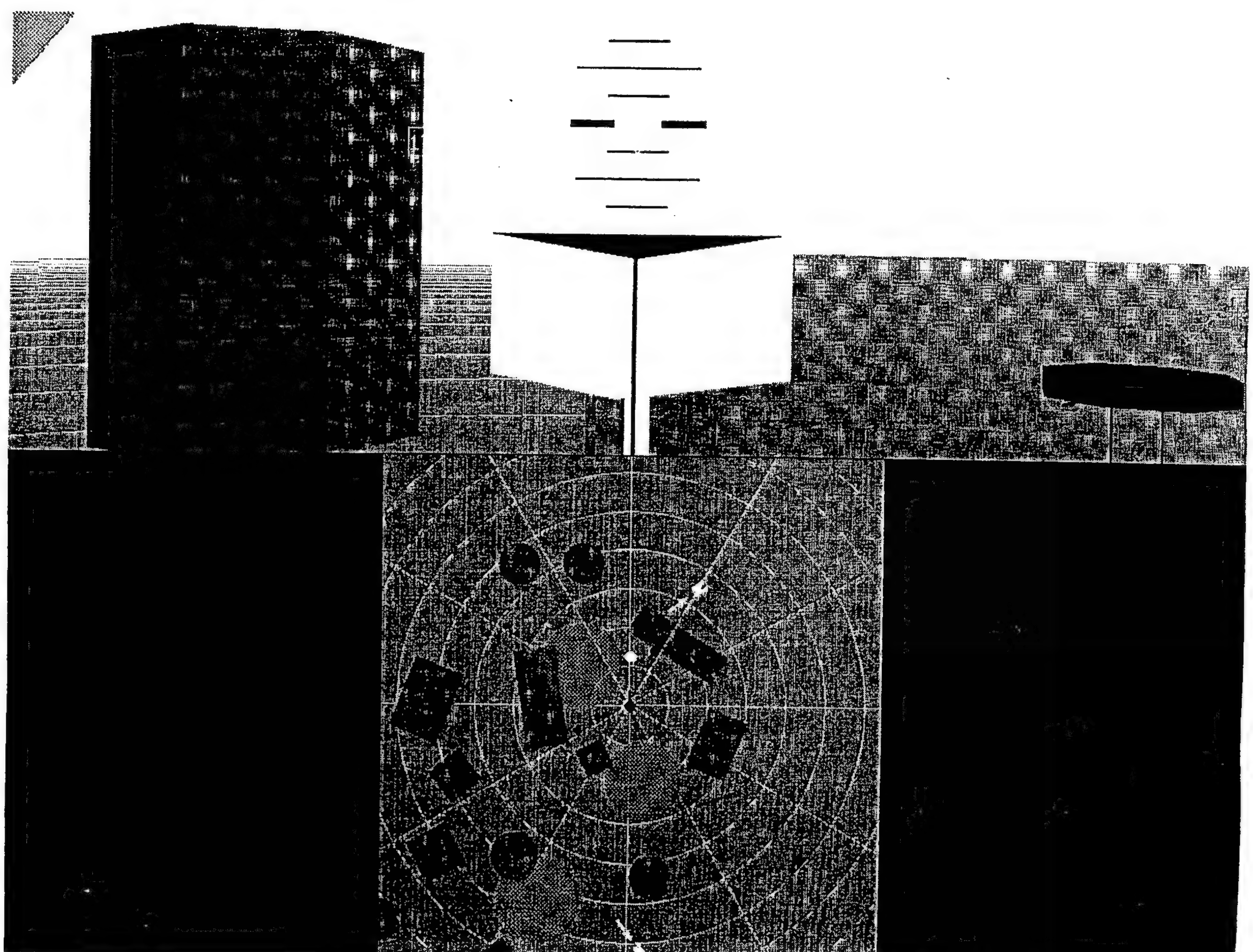
awareness would help pilots with global navigation planning and hazard location. However, a feature inherent in the top down planar view, is that there is minimal vertical resolution. To solve this problem, we chose to enhance the presentation of monoscopic depth cues.

Depth perception or spatial localization is mediated by different types of cues depending on the distance an object is from the eye. The monoscopic cue we chose to explore is relative size as an altitude discriminator for the plan view of the split screen display. Two studies found found that relative size cueing was just as effective as stereopsis in conveying information regarding differences in aircraft distance from the observer ((Mazur and Reising, 1990; Reising and Mazur, 1990).

Figure 1.13 (a picture of the SS display) illustrates the concept of using relative size in a top down planar display. Using ownship as the known size of an aircraft, pilots in the present study were asked to judge the relative altitude of intruders to ownship based on relative size. If the intruder size was larger than ownship, the intruder was higher (closer to the viewpoint). Conversely, a smaller intruder indicated a lower altitude relative to ownship. When judging changes in the intruder's vertical flight path, the pilots evaluated the change in the intruder symbol's size over time. If the intruder's symbol was increasing in size the intruder was climbing and vice versa for a descending intruder.

A second enhancement was made to the split-screen display to help pilots orient themselves as they transitioned between the immersed and plan views. Borrowing a concept from Woods (1984) we used visual momentum, by adding the wedge developed by Aretz (1990, 1991) to cognitively "tie" the two displays together. In the present study, we use the wedge to tie the plan view to the immersed view. We delineated the top 60^{o} sector (highlighting the 11:00 and 1:00 radials) in the plan view display to represent the area in that view seen in the top, immersed display in order to ease the transition from local to global awareness. For instance, the wedge was predicted to ease pilots orientation as they scanned between displays by delineating those objects within the confines of the wedge (tying their location to the immersed display) and their relative position to hazards outside of the immersed FOV. Additionally, the wedge was predicted to help pilots judge lateral and horizontal clearance when flying around or over a hazard by giving a shared frame of reference between the two display panels.

Figure 1.13: Screen shot of SS display: Low altitude intruder



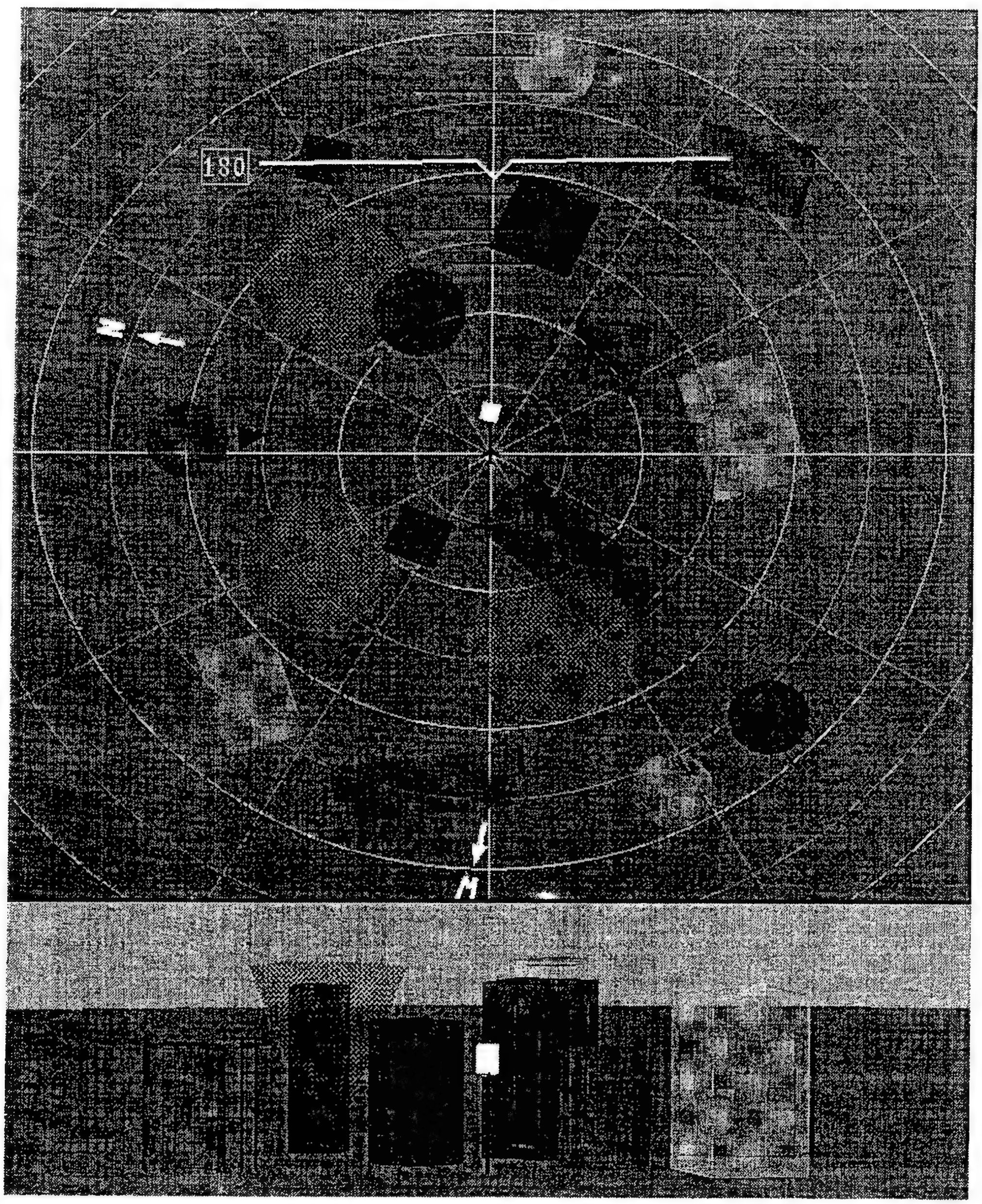
1.7.4 2D Coplanar Display Enhancements

Figure 1.14 is a picture of a 2D coplanar display used in the experiment. Visual momentum was also selected for use in the coplanar display to decrease the pilots' workload of orienting between displays. Previously, one of the VM techniques used in the coplanar display was the color coding of terrain hazards by altitude above the ground (Chudy, 1997). The color acted as a visual cue to tie the particular hazard objects in one display to the other. Also, the two displays were of different widths and the large number of objects presented in the display caused a clutter effect. Therefore, we chose to use a different VM technique in addition to the color cues. In previous studies, the bottom profile view was wider than the top plan view. The result was that there was not a direct vertical mapping of objects in the top view to their respective counterparts in the profile view. We narrowed the width of the bottom profile view and scaled both views so that there was a direct vertical linear mapping of objects. Because we aligned objects, the prediction was that pilots could more rapidly link the same objects between the two display panels. However, as a result of decreasing the width of the profile view, the density of the objects in the display increased such that resolving individual objects was difficult. To ameliorate the problem, the bottom display was adapted so that permanent objects (terrain and static air hazard volumes) that were within a 120^{o} arc behind ownship (8:00 radial to the 4:00 radial) were not displayed in the bottom, profile view. This modification significantly decluttered the profile view and made it easier for pilots to discriminate objects to the front and sides of ownship. Also, we believed that the removal of the vertical depiction of static information behind ownship, in no way, increased pilots' vulnerability to those hazards, since the hazard's location was still depicted on the top down display.

1.8 Summary

Overall, the goal of this study was to explore spatial enhancements to three display formats in order to assess their support of spatial situation awareness. The three displays, a 2D coplanar, 3D exocentric, and a 3D immersed/2D planar split screen display, were modified from earlier studies, by imposing object display and visual momentum enhancements. The 3D exocentric display was enhanced with object display enhancements targeted at improving the displays support of global spatial awareness of targets. The specific hypothesis was that object

Figure 1.14: Screen shot of 2D coplanar display



display elements, by nature of their shape and emergent features, would facilitate direct perception of relative altitude between ownship and an intruder. A secondary benefit would be the increased support for azimuth and distance judgments. Additionally, the predictor wedge and variable-geometry waypoints used by Chudy (1997) were employed to enhance local awareness and guidance.

The split screen display was modified to both increase the support for global spatial awareness of objects (relative altitude, azimuth, and distance judgments) and also local awareness and guidance judgments of lateral and vertical clearances required to avoid contacting hazards. The global awareness enhancements were implemented by the use of a top-down view global display with the addition of relative size monocular depth cues to discriminate relative altitude information and intruder altitude trend information. Visual momentum was used in the form of a wedge in the bottom plan view display to visually delineate the information viewed in the top immersed view. The prediction was that use of relative size cues in the 2D planar portion of the split-screen display would provide accurate relative altitude judgments. Also, the use of VM techniques, particularly the wedge to "connect" the top immersed display with the bottom planar display was inferred to provide improved local guidance as measured by contacts with hazards.

The modifications to the 2D coplanar display involved the employment of VM techniques in the form of color coding terrain hazards in both displays for altitude above the ground, and adjusting the scale of the bottom, profile view to achieve vertical alignment of objects in the top display with their counterparts in the bottom view. Coupled with the modification of decluttering the bottom profile view of permanent hazards in the 8:00 to 4:00 arc behind ownship, the use of the VM techniques was predicted to support both local awareness and guidance and global judgments.

2. Method

2.1 Subjects

Twenty four aviation students, all licensed pilots, from the University of Illinois Institute of Aviation participated in the experiment. Each pilot received a payment of $5.00 per hour. Pilots ranged in age from 19 to 33 and flight hours ranged from 100 to 3000. All pilots received the same set of instructions prior to starting the experiment.

2.2 Apparatus and Flight Dynamics

Pilots viewed display formats on a 16 inch diagonal screen run by a Silicon Graphics IRIS workstation. Pilots controlled aircraft pitch and roll with a two degree of freedom joystick attached to the right arm of the pilots' chair. The aircraft airspeed was set at 180 miles per hour (mph), in level flight. The pilots had no throttle controls. Standard flight dynamics were employed. If the pilot pushed forward on the joystick the aircraft pitched nose down and descended with a subsequent increase in airspeed to a maximum of 190 mph. If the pilot pulled back on the joystick the aircraft pitched up and the airspeed started to decrease to a minimum of 160 mph. The pilot rolled the aircraft to the right or left by moving the joystick to the right or left respectively. The turn rate was directly proportional to the roll angle. The flight dynamics were set so that pitch and roll were coupled. When the pilot entered a turn and rolled the aircraft it pitched down proportionately. The pitch and roll were restricted to 90 degrees per axis. There were no rudder controls.

2.3 Design and Procedures

This study used a within subjects repeated measures design. The twenty four subjects were randomly assigned to one of six groups. Each group was randomly assigned to one of six display condition orders. Pilots received written instructions regarding the purpose of the experiment and the tasks they were to perform. After they had read the instructions and were verbally queried for understanding by the experimenter, the pilots were seated in a darkened room in front of the IRIS display.

The pilots received three practice runs and three experimental trial runs in one day. They received a practice trial, lasting approximately five minutes, on each display format before

they ran the experimental trial for that particular display. The experimental trials lasted approximately 13 minutes. During the practice sessions, pilots were familiarized with the flight dynamics of the simulator and the experimenter ensured the pilots understood the different features of each display format and their tasks. Pilots were encouraged to fly the shortest possible route to the waypoint and to respond as accurately and quickly as possible to the spatial awareness tasks. After the practice sessions, the experimenter left the room and pilot initiated the start of the experimental trial.

Pilots judged eight intruder targets and two pop-up air hazards per display. The location of intruders and hazard volumes was altered for each experimental session with a new display.

2.4 Independent Variables

Display dimensions were manipulated so each pilot viewed the 2D Co-planar, the 3D Exocentric, and the 3D Immersed/2D Plan View split screen displays across three trials. The displays were manipulated with enhancements described in section 2.5. All pilots were exposed to all displays.

2.5 Displays

The world the pilots viewed was constant across all displays with respect to terrain and hazard volumes. All displays were oriented to track-up where the heading of the aircraft was always oriented at the top of the screen. The ground was green with a "dart board" grid arrangement. The center of the dart board was always directly below, and moved horizontally with, ownship. The radials were 30^0 apart to simulate clock positions; 12:00 being directly off the nose of ownship, 3:00 being at 90^o, etc. The range rings of the dart board were spaced 1 mile apart. Terrain was represented by wire frame, semi-transparent geometric objects of varying shape, height, and width. Air hazards and pop-up conflicts were represented as inverted black, semi-transparent cones of varying height and width. Navigation waypoints were represented as yellow flashing cubes with a vertical line attaching it to the ground.

Ownship was centered on the display (with the exception of immersed view in split-screen display) with equal viewing space in front and behind ownship. In order to facilitate inner-loop flight control, an attitude directional indicator (ADI) was presented at the

top of each display. A digital readout of airspeed was also presented to the left of the ADI for reference purposes. Ownship had an altitude pole anchoring it to the center of the dartboard.

Intruder aircraft were represented as redundantly shape and color coded objects; red triangle for foe, white square for friendly, blue circle for unknown. Each intruder had a "trail" depicting its trajectory history for the last 10 seconds and a heading pointer in the opposite direction of the trail to indicate current flight direction. The intruder symbols flashed at 5Hz until the pilot identified it with a button press. The intruder was removed from the screen after 30 seconds if the pilot had not pressed the ID button.

2.5.1 2D Co-planar Display Suite

This format consisted of two 2D displays arrayed vertically, one of which depicted horizontal information and the other depicted vertical information. Figure 1.15 illustrates the 2D co-planar display.

The top display, called the Horizontal Situation Display or "HSD", presented horizontal information using a top-down plan view with the viewpoint set 90° to the horizontal, looking straight down on world. The terrain on this particular display was color coded for absolute height above the ground: Gray = high, blue = medium, brown = low (Chudy, 1997).

The bottom display, called the Vertical Situation Display or "VSD", presented vertical information. The viewpoint was stationed at 180° azimuth looking along the line of flight. The display had the same width as the HSD in order to vertically align objects in the HSD with their counterpart image in the VSD.

Experimental Enhancements:

The VSD was changed so as to be the same width as the HSD. This vertically aligned objects in the VSD with their counterpart in the HSD.

2.5.2 3D Exocentric Display:

The 3D exocentric display, illustrated in figure 1.11, was a perspective display configured with an elevation angle of 30°, an azimuth of 8° right of ownship's tail, a tether length of 40000 feet, and a GFOV of 60°. Ownship was positioned in the center of the display and had a vertical predictor line connecting it to the center of the dart board.

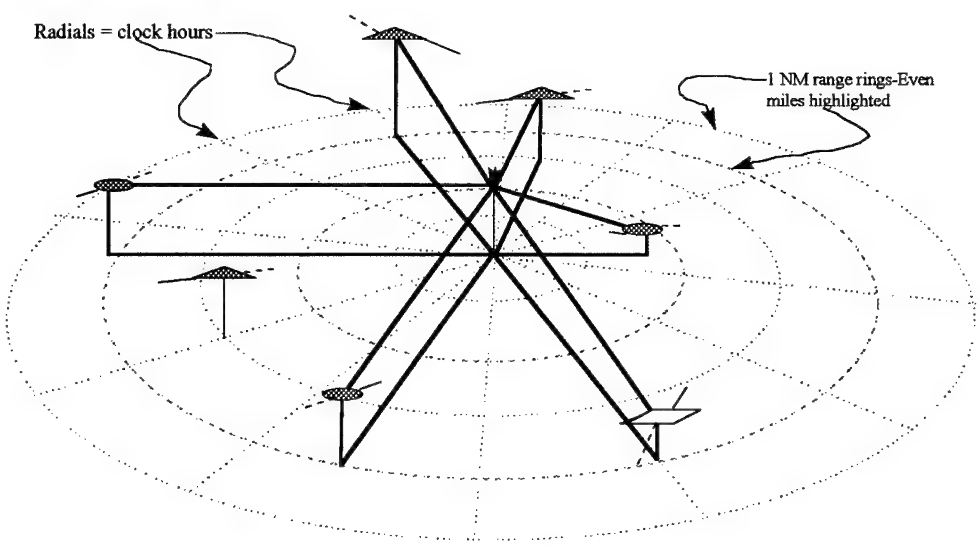
Experimental Enhancements:

Local Awareness/Guidance: Ownship had a flight path/lateral clearance predictor which was a white colored triangle extending 1.5 mile forward and 0.5 mile to each side of ownship. The apex of the predictor was attached to the nose of ownship. When the predictor penetrated a hazard it turned red until the hazard was cleared.

The waypoint cubes changed shape to direct the pilot to climb or descend to the correct intercept altitude. If the pilot was below the intercept altitude, the waypoint cube changed to an arrow pointing up. Once the pilot was at the correct altitude, the waypoint was depicted as a flashing cube.

Global Spatial Awareness: Object display elements were used to aid in pilot altitude, azimuth, and distance judgments of intruders as shown in figure 2.1. Lateral lines connected ownship and the intruder as well as their ground points. The lateral lines combined with the vertical predictor lines of both ownship and intruder to produce a polygon. The symmetry of the polygon indicated relative altitude and distance of intruder from ownship. Relative azimuth of intruder was indicated by the visual angle of the horizontal ground line from ownship to the intruder.

Figure 2.1: Exocentric display with different examples of intruders and object display elements.



2.5.3 3D Immersed/2D plan view split-screen Display Suite

The split-screen format consisted of two displays arrayed vertically as shown in figure 1.14. The top display was a 3D immersed perspective view with a 60 degree GFOV and 0 units of tether. The bottom display was a 2D plan view HSD with ownship in the center similar to the HSD in the 2D coplanar display suite.

Experimental Enhancements:

Local Awareness/Guidance: A wedge was incorporated into bottom display. The 11:00 (330°) and 1:00 (030°) radials on the bottom plan view were highlighted to coincide with the 60 degree horizontal field of view presented by the top immersed display.

Global Spatial Awareness: Intruder altitude information was represented by the use of relative size cues. Ownship was depicted as a diamond of specific size. Intruder aircraft were shape and color coded as previously mentioned but their size relative to ownship symbol varied with relative altitude. If the intruder's altitude was higher than ownship, the intruder symbol appeared larger than the ownship symbol and vice versa.

2.6 Tasks

In each condition, pilots were tasked to navigate as directly and as quickly as possible to the indicated waypoint. Only one waypoint was illuminated per leg and as soon as the pilot intercepted a waypoint the next waypoint appeared and flashed. There were eight waypoints 24,000 feet apart at random positions. Waypoint altitudes were varied in order to produce navigation legs requiring straight, vertical, lateral, and a combination of vertical and lateral maneuvers.

The eight legs within a display condition were designed to force the pilot to maneuver around terrain and air hazards to navigate to waypoints. There were 3 legs where a combination of lateral and vertical maneuvers were required to navigate to the waypoint rapidly, two legs which required predominantly vertical maneuvering, two legs which required mostly lateral maneuvering, and one leg which did not require substantial maneuvering. Once the eighth waypoint was intercepted the session terminated. The pilots were given the option of taking a break after each session was terminated and before they started a new session.

On every navigation leg an intruder appeared on the pilot's display at a preset time which was unknown to the pilots. Pilots were tasked to identify, with the press of button on the joystick, the intruder as a "friendly" or "foe/unknown". They then verbally judged the location of the intruder relative to their ownship in the following sequence:

1. Relative position to ownship by "clock" position, to the nearest 30 minutes. I.e., "7:00", "1:30"
2. Altitude relative to ownship: "High", "Level", "Low" Level was coded in the computer as ownship altitude ± 100 ft.
3. Distance from ownship in miles, to the nearest ½ mile.
4. Intruder's flight path relative to ownship: Will paths cross in front or behind ownship or not cross at all (intruder's heading is parallel or diverging)? "Front", "No-cross", "Behind"
5. Intruder's altitude change: "Climbing", "Level", or "Descending"

The pilots' responses were keyed into the computer by the experimenter. Response times and accuracy measures were computed and stored in the data files.

A pop-up hazard volume, depicted as black, translucent, inverted cone, appeared along the flight path in two of the legs on each display. The pilots task was to push a button on the joystick once they decided on an avoidance maneuver. The pilots' response times were recorded and their maneuver plotted to assess the effectiveness of their decision. One pop-up required a vertical avoidance maneuver and the other a lateral avoidance maneuver in order to intercept the waypoint in the shortest time.

2.7 Performance Measures

1. Intruder identification, location, and forecast: This measure was collected to assess each display format's ability to support global spatial awareness and judgment tasks. As mentioned in Tasks, the pilots responded verbally to intruder position and trajectory. The experimenter manually entered the pilots' responses into the computer as they were verbalized. The pilots then judged the future status of the intruder by predicting the intruders altitude change, if any, and whether or not the flight paths would cross. If the pilots predicted the flight paths would cross, they verbalized whether the intruder would cross in front of or behind ownship. These responses were manually entered into the computer by the experimenter.

The computer calculated reaction time and accuracy of pilots' responses by comparing them with the actual positions and altitudes of the respective aircraft. The ideal response was measured from ownship actual XYZ position at the moment the intruder appeared. Table 2.1 illustrates an example.

Table 2.1: An example showing pilot response and the error. Reported - Actual = Error

Intruder Loc.	Reported	Actual	Error
Azimuth	9:00	7:00	-2
Altitude	High	High	0
Distance	3	4	-1
Predicted Alt	Level	Descending	1
Crossing	1	-1	2

Response time for identification and location was recorded from intruder appearance to each response. Response time for prediction was recorded from last response for location to each prediction response. An overall RT. was also measured. There were eight intruder identification tasks for each display format.

2. Pop-up conflicts: This measure was collected to assess each display format's support for local awareness and guidance. At unexpected times on two legs of the navigation task, a hazard volume depicted as a black, semi-transparent inverted cone, appeared in the flight path. The pilots' task was to decide on a circumnavigation maneuver as quickly as possible. As soon as they made the decision, they pressed a button on the joystick. Response time was measured from the time the hazard appeared to the time the pilot pressed the joystick button. The accuracy of the decision was measured by the navigation time to the waypoint. A wrong maneuver decision would increase the navigation time.

3. Contact with terrain/hazards: This measure was collected to assess each display format's support for local awareness and guidance. The total number of terrain contacts and air hazard contacts were recorded for each leg. If a contact occurred, the pilot was alerted with a beeping tone. The tone terminated when the pilot maneuvered ownship out of the hazard. Contacts with terrain or air hazards would indicate deficient support for local awareness and guidance.

4. Total time for each leg: This measure was collected to assess each display's ability to support local guidance and awareness. Timing commenced for individual legs when the next waypoint started flashing and ended when the pilots intercepted the flashing waypoint. Subjects were encouraged to fly the shortest route possible to each waypoint while avoiding contacts. Excessive times would indicate local guidance deficiencies.

5. Flight Path position: Ownship's XYZ position was recorded every five seconds. XYZ position was recorded to later assess qualities of the avoidance maneuvers. Also, XYZ position was recorded to allow reconstruction of the flight path for analysis of contacts.

3. Results

The data were analyzed using the statistical computer program SPSS for Windows version 6.1. Prior to analysis, dependent variable means were calculated and plotted. In order to identify any outliers, while still preserving data, total navigation time, total absolute error, and total response time were calculated for each subject and averaged across subjects. Cases which were outside ±3 standard deviations of the mean for each respective total (navigation time, error, and response time) were excluded from analysis. This resulted in 13 cases out of 576 being excluded from analysis. The exclusion of the outliers from the navigation time analysis also removed those cases (3 identified) which were abnormally high due to a computer timer malfunction.

The results are reported in two sections, Local Spatial Awareness and Guidance Measures, and Global Spatial Awareness Measures. Conditions specific to each portion of the results analysis are reported in each section.

3.1 Local Spatial Awareness and Guidance Measures:

Local guidance measures were navigation time from waypoint to waypoint and the number of contacts with air hazard volumes and terrain hazards. Local awareness measures were the time it took pilots to detect popup air volume hazards and the time it took them to maneuver around the air hazard to the waypoint.

3.1.1 Local Guidance Measures:

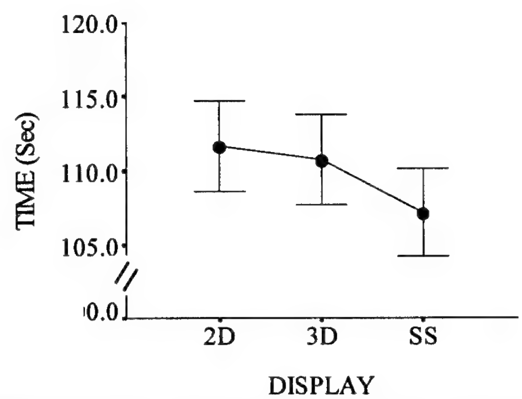
Total Navigation Time

Total navigation time is defined as the interval of time between when pilots intercepted one waypoint and when they intercepted a subsequent point. Because of the display configuration with the exocentric (3D) display, there were some navigation legs where a waypoint was intercepted and the next waypoint was not visible on the screen. When the next waypoint was not visible, the pilots randomly chose to turn left or right. On those occasions on which the pilots chose to turn in the wrong direction (i.e., well over 180^{o}), the time it took them to turn to their new intercept heading was subtracted from the time it would have taken them to turn in the opposite direction directly toward the next waypoint. The resulting difference was

then subtracted from the navigation time for that particular leg. This recalculation was carried out for 31 of the 183 legs flown with the 3D exocentric display. Recalculating the leg times resulted in an overall decrease of 1.3 seconds for the mean navigation time for the 3D exocentric display.

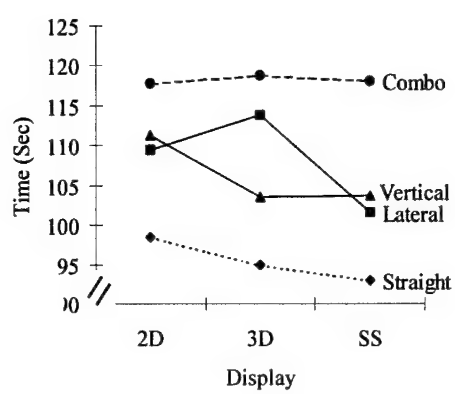
The total time to navigate through each display was then analyzed in a 3 levels of display by 4 levels of maneuver repeated measures ANOVA. The analysis revealed a marginally significant main effect of displays ($F_{2,23}=2.966$, $p<0.072$). (See Figure 3.1) Planned contrasts between the three displays revealed a significant cost in navigation time for

Figure 3.1: Total Navigation Time



the coplanar (2D) display relative to the split screen (SS) display ($F_{1,23} = 6.20$, $p<0.020$). There was not a statistically significant difference in navigation times between the 2D display and the 3D display nor the 3D display and the SS display. Figure 3.2 shows the main effect of maneuver on navigation times ($F_{3,22} = 35.67$, $p< 0.001$) and a significant display by maneuver

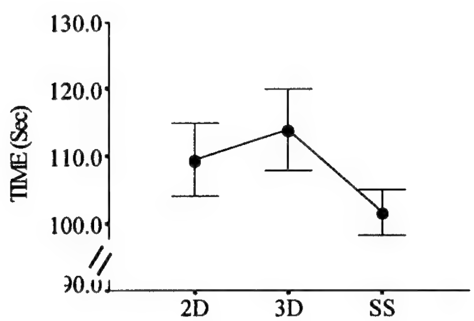
Figure 3.2: Maneuver Times



interaction ($F_{6,18} = 3.59$, $p < 0.016$). Analysis of the interactions revealed that, of the four maneuvers accomplished with each display, straight, lateral, vertical, and combination, two maneuvers, lateral and vertical, showed simple main effects of display. These effects are discussed below.

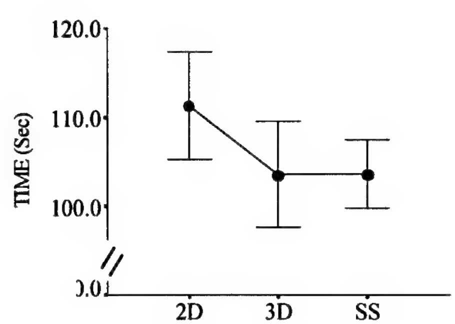
Lateral Legs: (Figure 3.3) There was a significant effect for display type when navigation required pilots to maneuver laterally to reach the waypoint in the shortest time ($F_{2,22} = 5.718$, $p<0.01$). Contrasts between the displays revealed that the SS display supported faster navigation times then either the 2D display ($F_{1,23}=4.965$, $p<0.036$) or the 3D display ($F_{1,23}=8.745$, $p<0.007$).

Figure 3.3: Lateral maneuver navigation times



Vertical Legs: Navigation legs which required vertical maneuvering to reach the waypoint in the quickest time showed an effect of display ($F_{2,22}=3.755$, $p<0.04$) as seen in figure 3.3. Both the 3D and SS displays supported faster vertical navigation legs than the 2D display, ($F_{1,23}=6.927$, $p<0.015$) and ($F_{1,23} = 5.934$, $p<0.023$) respectively.

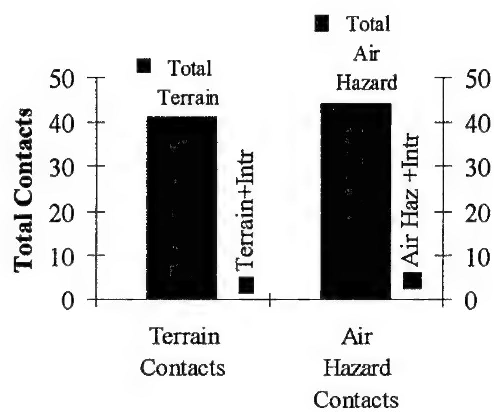
Figure 3.4: Navigation time for legs requiring vertical maneuvers



Contacts with Hazard Volumes

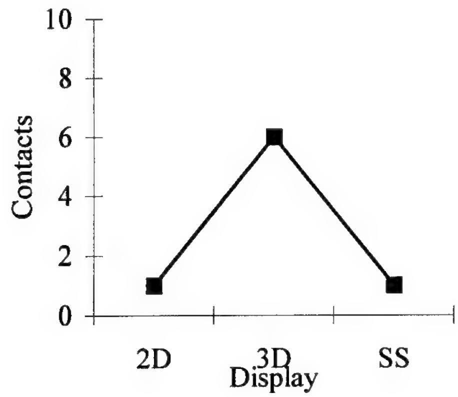
The total number of contacts and the number of air hazard contacts and terrain contacts were analyzed separately. There were no significant effects of display or maneuver type on the number of contacts, and the total number of contacts was quite low. However, it was noted by the experimenter that most of the contacts occurred while pilots were verbally reporting intruder information. Therefore, an analysis was done post hoc to ascertain if there was an effect of intruder presence on collisions. The flight path plots were examined for those legs on which collisions occurred and 58% of contacts with hazards occurred when an intruder was present. When terrain contacts and air hazard contacts were analyzed (See Figure 3.5), 51% of terrain contacts and 64% of air hazard contacts occurred during the relatively small proportion of time

Figure 3.5: Terrain and air hazard contacts



when an intruder was present. This indicates that the presence of an intruder may have reduced the navigation performance of those pilots who contacted a terrain or an air hazard volume. Analysis of the hazard contact data when an intruder was ***not*** present revealed that the number of air hazard contacts was slightly higher than the number of terrain contacts. In particular, there was a marked increase in the number of air hazard contacts on those legs with lateral maneuvers for the 3D display (Figure 3.6) The higher number of lateral contacts in the 3D display is consistent with findings by Boyer, Campbell, May, Merwin, and Wickens (1995) and Merwin and Wickens (1996) which indicated that the 3D display does not afford as good lateral clearance judgment as does the 2D display format.

Figure 3.6: Air hazard contacts for lateral maneuvers when intruder NOT present



3.1.2 Local Awareness Measures:

Analysis of the local awareness measure of detecting a popup air hazard volume revealed no significant effects for popup hazard response. Additionally, the time it took for pilots to circumnavigate the hazard volume was not significantly different across the displays.

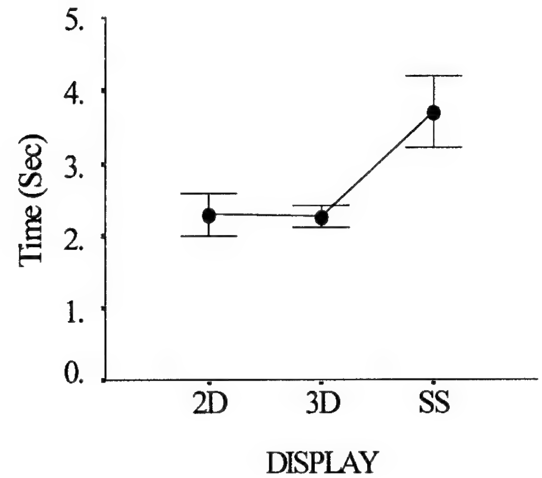
3.2 Global Spatial Awareness Measures

Global spatial awareness judgments (mean absolute error, MAE) and response times (RT) regarding the intruder aircraft's "identity friend or foe" (IFF), relative azimuth (Az), relative altitude (Alt), and distance (Dist) from ownship were analyzed to evaluate the displays' support for current spatial judgments. Judgments and RT's regarding intruder - ownship flight path intersection (HPath) and intruder's altitude change (VPath) were analyzed to assess the displays' support of trend information.

3.2.1 Effects of Display:

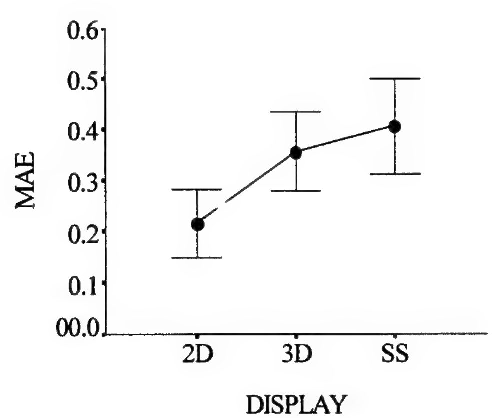
Intruder ID RT (Figure 3.7): Analysis showed a main effect for display ($F_{2,22}=15.969$, $p<0.001$). The 2D coplanar display and the 3D exocentric display showed no difference in IFF RT. IFF RT's for the SS display were slower than both the 2D display ($F_{1,23}=29.896$, $p<0.001$) and the 3D display ($F_{1,23}=29.511$, $p<0.001$).

Figure 3.7: Intruder IFF RT



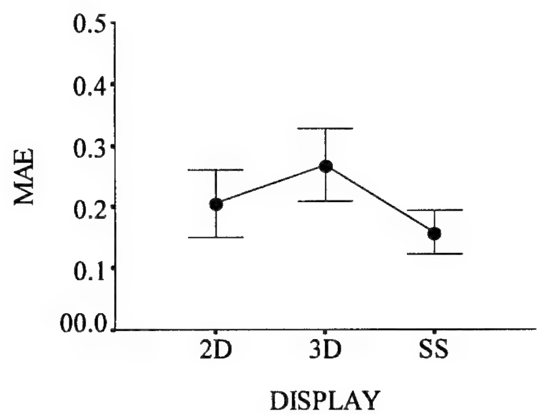
Intruder Altitude Judgments (MAE) (Figure 3.8): There was a main effect of display on the accuracy of altitude judgments ($F2,22=11.675$, $p<0.001$). Further analysis showed that altitude judgments made while flying with the 2D coplanar display were more accurate than those made with the SS display ($F1,23=14.168$, $p<0.001$) and the 3D display ($F1,23=10.714$, $p<0.003$). There was not a statistically significant difference between performance with the 3D and SS displays.

Figure 3.8: Intruder Altitude Judgment Error



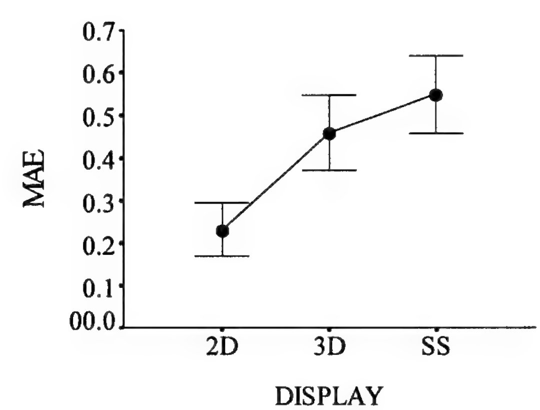
Intruder Distance Judgments (MAE) (Figure 3.9): Analysis revealed that there was a main effect of display for intruder distance judgments ($F_{2,22}=3.614$, $p<0.044$). The SS display supported more accurate distance judgments than did the 3D display ($F_{1,23}=7.49$, $p<0.012$). There were no statistically significant differences between the 2D display and either the SS display or the 3D display.

Figure 3.9: Intruder distance judgment error



Intruder Altitude Change (VPath) Projection (MAE) (Figure 3.10): The altitude change projection analysis showed a significant effect of display ($F_{2,22}=11.271$, $p<0.001$). Projections made while flying the 2D coplanar display were more accurate than either the 3D display ($F_{1,23}=12.389$, $p<0.001$) or the SS display ($F_{1,23}=15.749$, $p<0.001$). The MAEs between the 3D and SS displays were not statistically different from each other.

Figure 3.10: Intruder Altitude Change Judgment Error

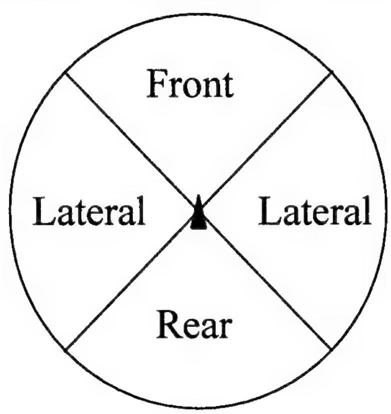


The other global awareness measures regarding relative azimuth and horizontal path trajectory were not found to differ significantly between conditions.

3.2.2 Detailed Analysis of Performance with the 3D Exocentric Display:

A separate analysis by target sector was accomplished focusing on the 3D exocentric display to ascertain the effectiveness of the object display enhancements. This analysis was performed because of differences in the way the object enhancements represented altitude when viewed parallel with or orthogonal to the viewing axis. The reason for this difference was the projection geometry of in the 3D graphics display. Because perspective rather than parallel geometry was employed , it is apparent that two aircraft at the same altitude would not generate parallel lines (Figure 1.13) if they were in the front or rear sector, as they would in the lateral sectors. Hence, we expected a possible affect of sector on altitude judgments. Figure 3.11 depicts the sector divisions. The "Front" sector was defined as being 45° on either side of the forward flight path (from the 10:30 radial to the 1:30 radial). The "Rear" sector was defined as

Figure 3.11: Sector Divisions

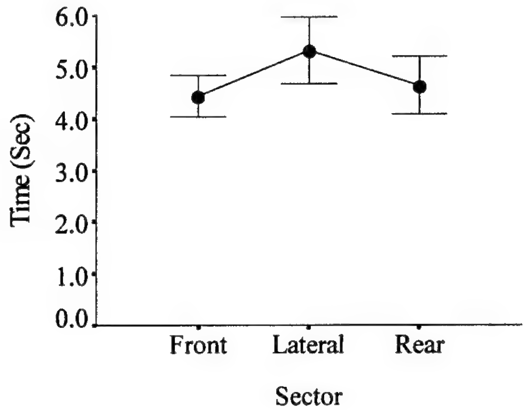


the quadrant between the 7:30 radial and the 4:30 radial. The remaining sector called the "Lateral" sector, was comprised as the two 90° sectors to the side of the flight path. The two lateral sectors were combined since both would be equally able to show parallel lines for equal altitude.

Intruder Azimuth RT (Figure 3.12): There was a main effect for sector in the 3D display ($F_{2,22}=6.455$, $p<0.006$). Analysis revealed that intruders appearing in the lateral

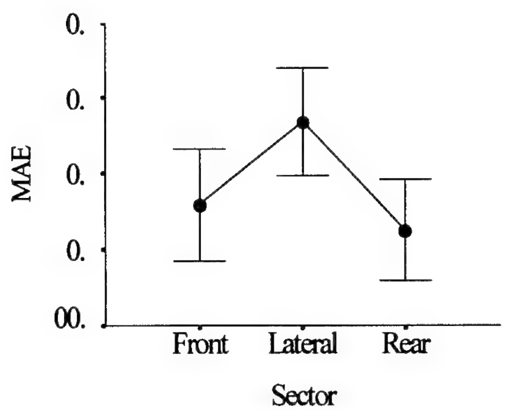
sectors were detected more slowly than the intruders which appeared in either in the front ($F_{1,23}=6.113$, $p<0.021$) or the rear sector ($F_{1,23}=8.875$, $p<0.007$).

Figure 3.12: 3D Azimuth Judgment RT



Intruder Azimuth Judgment (MAE) (Figure 3.13): The sector in which an intruder appeared had a main effect on azimuth ($F_{2,22}=7.668$, $p<0.003$). There were smaller errors of azimuth judgment when intruders appeared in the front sector ($F_{1,23}= 4.189$, $p<0.052$) and rear sector ($F_{1,23}=15.095$, $p<0.001$) than when they appeared in the lateral sectors. No other dependent variables were effected by sector in the 3D exocentric display.

Figure 3.13: 3D Azimuth Judgment Error

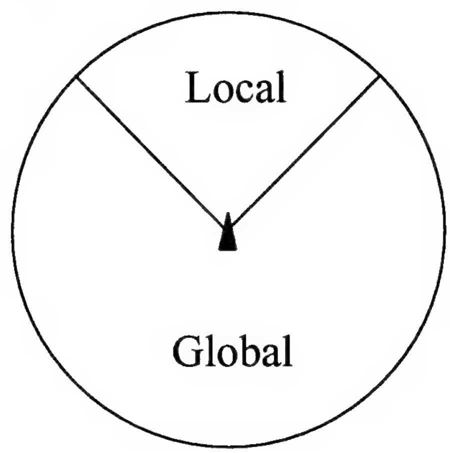


3.2.3 Detailed Analysis of the Split Screen Display

An additional analysis was performed on the split screen display suite because of the unique nature of the top-down 2D plan view global display. Due to the poor vertical resolution of the plan view, relative size was used to provide vertical cues for intruder altitude judgments

and intruder altitude change prediction. This meant that intruder judgments were made on the basis of two qualitatively different information sources depending on whether or not the intruder was visible in the immersed display of the SS display suite in which case altitude could be judged directly by the vertical position of the aircraft symbol. If the intruder appeared in any other sector, then its altitude could only be judged by the size of the symbol. For this reason, the data were analyzed in terms of two sectors (See figure 3.14). The first sector is defined as 45° to each side of the forward flight path (10:30 radial to the 1:30 radial) and is called the <u>local</u> sector. The second sector is the remaining 270° of the display and is called the <u>global</u> sector. The split screen suite analysis examines the effect of sector on the global awareness measures in two stages; by sector alone (Table 1) and then by sector and intruder altitude (High-Table 2, Low-Table 3). The two tables at the end of this section present the means for each measure.

Figure 3.14: SS display sectors



Sector Analysis: Table 3.1 depicts the means and their associated t-statistics comparing judgments based on intruders in the global versus the local sector for the statistically significant measures. The RT means are in seconds and the AE means are MAE units. Faster IFF RT and more accurate judgments regarding vertical position and trend of the intruder were observed in the local sector relative to the global sector. In contrast, there were fewer errors and faster RT's for the lateral judgments regarding intruder-ownship path crossing (HPath) if the intruder appeared in the global sector than the local sector. According to these results, judgments regarding vertical position and vertical change were more accurate in the local sector while projections of the intruder's lateral path were more accurate in the global sector.

Table 3.1: Sector Analysis of Means

	Means			
Measure	**Local**	**Global**	$t_{2/188}$	α
ID RT	2.98	3.94	-2.031	0.044
HPathRT	3.78	3.07	2.399	0.017
Alt AE	0.24	0.46	-2.022	0.045
HPathAE	0.96	0.60	2.511	0.013
VPathAE	0.33	0.62	-2.944	0.004

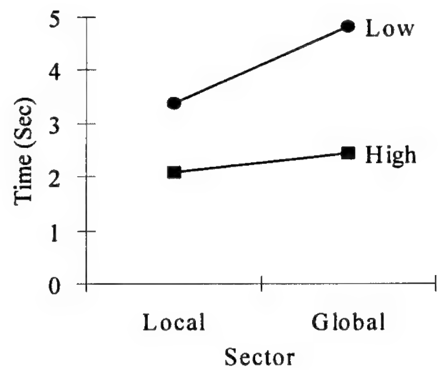
Sector by Intruder Altitude Analysis: Because of the display enhancements to the SS display explained above, we were interested in the affect that intruder altitude would have on spatial awareness judgment errors. It was expected that low altitude intruders appearing in the local sector would be detected faster and have smaller errors than if they appeared in the global sector because of their small size in the latter case. Therefore, the data was analyzed by intruder altitude to see what differences, if any, existed between high and low altitude intruders if they appeared in the local or global sector.

Due to the fact that the pilots were not restricted to a specific flight path but were free to navigate to the waypoints using their best judgment, some anomalies in the data appeared. The experimental design planned for an equal distribution of intruders at high, level, and low relative altitudes to ownship. The resulting data for the SS display, however, had a preponderance of low altitude intruders (121) relative to high altitude intruders (64) and level intruders (5). Therefore, the raw data regarding actual altitude differences in feet between ownship and intruder were analyzed and the level intruders were reclassified into either the high or low altitude categories. Reclassifying the level intruders resulted in roughly twice the number of low altitude intruders (123) as there were high altitude intruders (67). Further division of the intruders into sectors resulted in 34 low altitude intruders in the local sector and 89 intruders in the global sector. For high altitude intruders, 15 of them appeared in the local sector and 52 appeared in the global sector.

Intruder Identification Friend or Foe (IFF) RT: IFF RT was included in the analysis because we were interested in the effectiveness of flashing as an attention guidance cue in the SS display. Figure 3.15 depicts the RT's for both the high and low altitude intruders which shows that RT's for low intruders were generally slower than for the high altitude intruders.

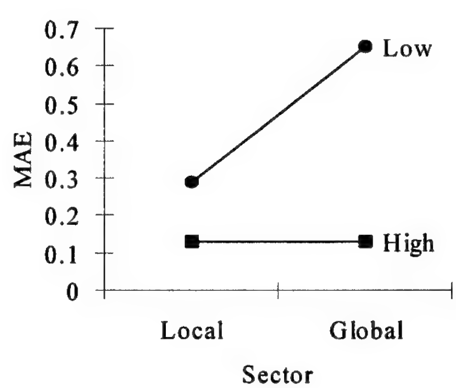
Low altitude intruders were responded to significantly faster when the intruder appeared in the local sector than when they appeared in the global sector ($t_{2/121} = -2.06$, $p < 0.05$). For high intruders, the RT difference between the local and global sector was not significant.

Figure 3.15: IFF RT



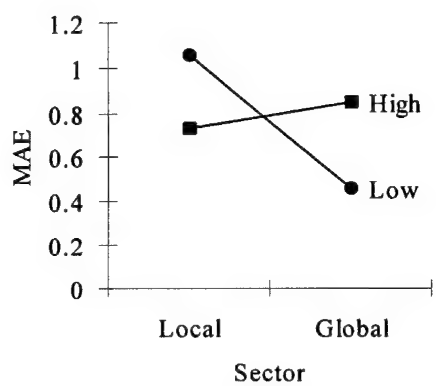
Intruder Altitude Judgment Error (MAE) (Figure 3.16): Relative altitude judgments of the low altitude intruder showed the same pattern as for IFF RT's. Judgments were more accurate when the intruder appeared in the local sector than when they appeared in the global sector ($t_{2/81.6} = -2.95$, $p < 0.01$), while there was not a significant difference between sectors for the high altitude intruders.

Figure 3.16: Altitude judgment error



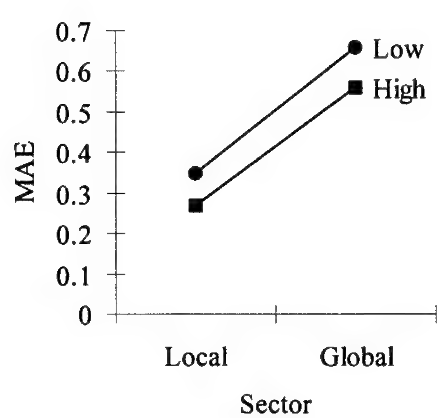
Intruder-Ownship Flight Path Intersection Projection Error (HPath) (Figure 3.17): The projections of whether or not the intruder will cross in front of, in back of, or not cross flight paths with ownship were more accurate for low altitude intruders when they appeared in the global sector ($t_{2/47.3} = 3.23$, $p < 0.01$). When the intruder appeared at high altitude, these errors did not differ as a factor of sector.

Figure 3.17: HPath Error



Intruder Altitude Change Projection (VPath) (Figure 3.18): Pilots projected the intruder's change in altitude more accurately when the intruder appeared in the local sector than the global sector for both the low altitude intruders ($t_{2/121} = -2.45$, $p < 0.02$) and the high altitude intruders ($t_{2/29.7} = -2.01$, $p < 0.06$).

Figure 3.18: VPath Error

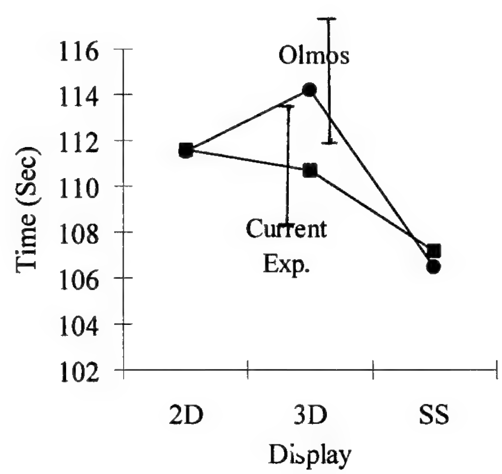


In summary, the sector analysis applied to the SS display suite revealed that different altitude cues were extracted depending on whether or not the intruder appeared in the front sector (visible in the immersed display). In this case, altitude was perceived using the high, linear, resolution of vertical cues afforded by the immersed display and was, therefore, judged more accurately. Presumably, however, pilots also used this view, rather than the bottom display which provided more precise horizontal cues, to judge the intruder's behavior regarding the horizontal axis. As a consequence, horizontal judgment accuracy suffered because the longitudinal (Z axis) was not well represented in the immersed view. In contrast, when intruders appeared in the global sector, intruder altitude judgments suffered disproportionately more when intruders were low (small symbol) than when they were high (large symbol) and when absolute altitude (figure 3.16) was to be judged. Also, overall judgment accuracy regarding intruder altitude change trends suffered (figure 3.18) when the only altitude cue was the absolute size of the symbol (small for low, large for high).

4. Discussion

The goal of this experiment was to assess the effectiveness of spatial enhancements to improve the ability of a 2D coplanar display suite, a 3D exocentric display, and a split-screen (SS) display suite to support local guidance and both local and global spatial situation awareness. In the following sections, we evaluate the effectiveness of the enhancements compared to the support provided by displays used in Olmos (1997) upon which the current displays are based. We then consider how the enhancements used in the current displays effected each display's support for spatial awareness relative to the other two display formats within the context of the current experiment. Figure 4.1 shows the comparison of local guidance task support performance of the three displays between Olmos (1997) and the current experiment.

Figure 4.1: Comparison between Olmos (1997) and current experiment of local guidance task performance (Navigation times). (Note: Error bars represent ±2 S.E.'s = 95% C.I.)



4.1 2D Coplanar Display Suite:

Olmos' 2D coplanar display suite was modified with the implementation of visual momentum by reorienting the bottom, vertical situation display (VSD) by 90^{o} so that objects were vertically aligned with their counterparts in the top horizontal situation display (HSD).

The modifications made to Olmos' 2D displays, had little affect on overall local guidance when total navigation times were considered.

Overall, there was a cost - benefit tradeoff for local guidance between Olmos' 2D display and the 2D display used in this experiment. In order to implement the VM technique, the VSD in the current display was scaled down in order to match the width of the HSD. This change decreased the display area and the size of objects, especially that of ownship, within the VSD which resulted in greater density and perceived clutter regarding vertical navigation information (which was only supported by the bottom, compressed, display). We surmise that pilots had difficulty in continually assessing the vertical position of ownship relative to hazards in the flight path, making it harder for them to plan an optimal route to the waypoint for legs where the optimal route required vertical maneuvers and, thus, the use of the VSD. Olmos' VSD, on the other hand, was wider and, therefore, had less apparent visual density making navigation path choice easier despite the orientation of the VSD being orthogonal to the line of flight depicted in the HSD.

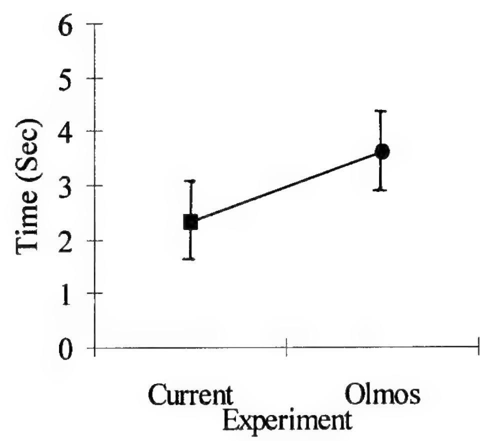
Thus, the hypothesized benefit for vertical navigation of moving the azimuth angle of the VSD to 0^{o} was offset by the decrease in size of the VSD. We think, having interviewed pilots after they used the display, that increasing the size of ownship's symbol would ameliorate most of this problem by making it easier to see.

The enhancements made to increase the coplanar display's ability to support global spatial awareness were targeted mainly at judgments regarding the vertical axis which required pilots to scan from the HSD to the VSD. The only situation awareness task shared by the two experiments allowing us to make this comparison was that of intruder altitude judgments.

There were no differences between Olmos' 2D coplanar display and the current 2D coplanar display with regard to altitude judgment accuracy. This is not surprising since the vertical resoiution on each VSD was unchanged with the change in viewpoint azimuth angle between the two experiments. There was, however, a difference in the altitude judgment response times shown in figure 4.2. The current display clearly supported faster altitude judgment response times in both comparison to Olmos' display and to the 3D exocentric display in the current experiment. We think that using the VM technique of reorienting the

VSD reduced both the physical and cognitive distance between the representation of the target in the

Figure 4.2: Comparison between the current and Olmos' 2D coplanar displays' support for Intruder Altitude Response Times.



HSD and the VSD, as predicted by the Proximity Compatibility Principle (Wickens and Carswell, 1995). This, in turn, allowed pilots to make faster, but just as accurate, altitude judgments. Therefore, the conclusion was reached that the VM technique did indeed decrease the information access cost within the 2D coplanar display suite and was effective in increasing the 2D coplanar display suite's support for global spatial situation awareness.

4.2 The 3D Exocentric Display

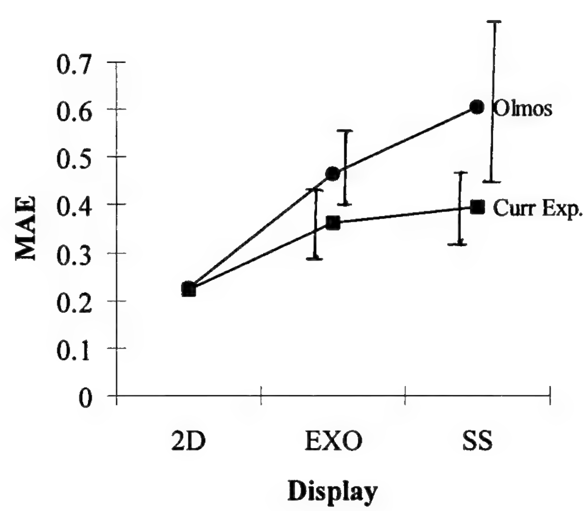
The enhancements made to the 3d exocentric display to assist local guidance had positive results when compared to Olmos' results as shown in figure 4.1. The overall navigation times for the current experiment dropped primarily as a result of the decreased times for vertical navigation legs. Modifying the waypoint cubes to command a climb or descent to the correct waypoint intercept altitude disambiguated the vertical navigation confusion that Olmos reported occurred as the pilots flew closer to the waypoint. As a result, the navigation times were faster because pilots using the current 3D exocentric display did not miss as many waypoints by flying over or under them. This increase in vertical navigation performance could also have been effected by the predictor wedge described in section 1.6.5. The wedge's color

change gave pilots cues as to both their distance and projected vertical clearance over or under hazards which helped enroute planning.

There were no differences in the navigation times between Olmos' and the current study in lateral leg navigation times. This indicates that the change in viewpoint azimuth angle, from 15° to 8° was not sufficient to ameliorate the lateral ambiguity of the 3D exocentric display. This finding supports findings by Ellis, Kim, Tyler, McGreevy and Stark (1981) and Wickens, Liang, Prevett, and Olmos (1994) which indicated that changing the azimuth angle between 0° and 45°, while holding the elevation angle constant, does not change lateral tracking performance. Therefore, it is possible that in order to increase the lateral navigation cues in a 3D display, a combination of azimuth and elevation angle changes need to be explored to find an optimum set of angles for lateral navigation information while still maintaining adequate vertical axis resolution. The predictor wedge was also designed to help with lateral navigation by helping pilots predict lateral clearance from hazards. However, it appears from the results, that the cues the wedge provided were not sufficient to override the overall ambiguity regarding lateral guidance information in the 3D exocentric display.

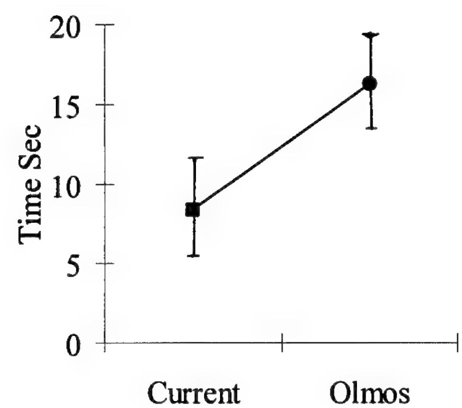
The enhancements made to Olmos' 3D exocentric display to improve global spatial situation awareness also had positive benefits. The enhancements, in the form of object displays described in section 1.7.2, were designed to support the judgments of bearing, altitude, and distance to the intruder. When compared to Olmos' results, it appears the use of object displays significantly improved the accuracy of altitude judgments (See figure 4.3). These results indicate that the use of object display elements in a perspective display have benefits in

Figure 4.3: Altitude judgment error: Olmos compared to current experiment.



disambiguating the altitude-distance confusion observed in the unaugmented 3D perspective displays. Thus, in summary, the 3D exocentric display used in this experiment showed improvement over Olmos' display in both local guidance and global spatial situation awareness due to the enhancements made to decrease the costs of the 3D exocentric format ambiguity.

Figure 4.4: Intruder detection times for the current experiment's SS display suite and Olmos' SS display suite.



4.3 The Split Screen Display Suite

The enhancements made to the SS display suite focused on the bottom, global awareness display by changing it from a 3D exocentric view used by Olmos to a top down plan view HSD similar to the one used in the current 2D coplanar display suite. It appears that, in this experimental paradigm, the use of the relative size cues to spatially represent the vertical axis in a 2D HSD resulted in better altitude judgments of targets not in the forward field of view than were observed for Olmos' global awareness display (See figure 4.3). This advantage is inferred to be a result of the relative size differences being easier to distinguish than the altitude differences represented by the different heights of ownship's and the intruder's altitude poles in Olmos' unaugmented 3D format. Additionally, as shown in figure 4.4, when compared to Olmos' SS display, the use of flashing as an attention guidance cue, was effective in drawing attention to the HSD as measured by the reduced amount of time it took to detect the presence of an intruder in the current experiment. Therefore, the conclusion revealed by this comparison was that the HSD used in the current experiment overcame the global spatial awareness

problems in Olmos' SS display suite without hindering the superior guidance fostered by the top, egocentric, display.

4.4 Comparative Analysis of the Three Display Formats.

While all three of the basic display formats were enhanced in this experiment to try to remediate their weaknesses, in this final section we consider the three displays comparatively to determine if residual signs of the weakness and strengths remain. We address these in terms of three features that discriminate among the displays: (1) ambiguity contrasts between both the 3D exocentric display and the 3D immersed display of the SS display suite with the 2D coplanar display suite; (2) scanning, or selective attention effects, contrasting the integrated exocentric display with the two 2-display "suites" (SS and coplanar); (3) the effect that frame of reference (egocentric and exocentric) has on display performance which contrasts SS (egocentric) with the two exocentric views (the 3D exocentric and the 2D coplanar displays).

Ambiguity: As we noted in the Introduction, one of the characteristics of projecting a 3D image onto a 2D display is ambiguity as to the true spatial relationships between objects within the display (Ellis and Hacisalihzade, 1990; McGreevy and Ellis, 1988; Merwin and Wickens, 1996; Olmos, 1997; Wickens, Liang, Prevett, and Olmos, 1995). In this experiment, costs incurred by ambiguity still plagued the 3D display in terms of support for local guidance. As shown in figure 3.3, the 3D exocentric display did not support lateral navigation maneuvers as well as the other two display formats. The findings also support findings by Boyer, May, Campbell, and Wickens (1993) who reported that the 3D exocentric display format did not provide as precise lateral navigation cues as that of a 2D display. The conclusion that lateral navigation costs were not eliminated was also supported by the finding that the number of air hazard contacts for lateral legs were higher for the 3D exocentric display than the other two display formats (See figure 3.6).

Additionally, both of the 3D displays used in this experiment (the 3D exocentric display and the immersed display in the SS display suite) showed residual ambiguity related costs for global spatial situation awareness tasks, in spite of the implementation of enhancements. The use of object display enhancements in the current 3D exocentric display was not sufficient to fully compensate for the 3D ambiguity cost, in the judgment of altitude (figure 3.8), altitude change (figure 3.10), or distance (figure 3.9) when compared to the 2D coplanar display or SS

immersed display formats. A possible reason for the failure of object displays to completely disambiguate the 3D exocentric display in this particular experiment was the use of a perspective, rather than a parallel, projection. The parameters used to induce a perspective view and the resulting spatial cues provided by the perspective projection could have disrupted the validity of using parallellity as an invariant cue to gauge equal altitude in all sectors. A more detailed analysis of the data, by sector, did not enlighten us as to the reason why the object displays did not fully compensate for the ambiguity effect. For example, we had reasoned that perspective geometry would play less of a role when intruders appeared in the lateral sectors (intruder and ownship at equal viewing distance) but this was not found to be the case. It will probably be necessary to run an additionally study, with new subjects using parallel geometry, in order to evaluate this hypothesis. Therefore, as mentioned in section 4.2, while the use of object displays helped decrease altitude-distance ambiguity, the benefit of the object displays did not eliminate all of the costs inherent in the 3D exocentric format when compared to the current 2D coplanar display suite.

When vertical judgment performance with the 3D exocentric display is compared with that of the SS display suite, the results are mixed. When intruders appeared in the lateral and rear sectors, thus not visible in the SS suite's immersed display, then the ambiguity of the 3D exocentric display was balanced by the low resolution of the size changes in the SS HSD. Therefore, neither the 3D exocentric or the SS display suite provided good vertical judgment cues when compared to the 2D coplanar suite. However, when the intruder appeared in the front sector, and was visible in the immersed display, the high resolution of the vertical axis in that display gave it a major advantage over the ambiguous 3D exocentric display.

Additionally, the weakness of the 3D exocentric display's ability to support global spatial awareness was evident for horizontal judgment accuracy, seen primarily in distance judgment accuracy (Figure 3.9). When the accuracy of judgments concerning events on the horizontal axis are considered, both the 2D and SS HSD's supported more accurate assessments than did the 3D exocentric display. This finding is attributed to the precision with which the HSD's of both the 2D coplanar suite and the SS display suite presented distance and horizontal trend information. Thus, the intersection of the ground vector with the intruder's altitude vector in the object display did not eliminate enough horizontal judgment cost.

Another manifestation of ambiguity was seen in the analysis of performance by SS display sector (Table 3.1). When intruders appeared in the global sector, thus not visible in the immersed display, judgment accuracy of their horizontal position and trajectory were high, compared to when they appeared in the local sector and were visible in both the immersed display and the HSD. We assume that the degraded performance in the latter case was a result of the pilots making distance judgments only on the basis of the impoverished monocular depth cues along the immersed display's line of sight, rather than referring to the unambiguous HSD for more accurate judgments. Why they failed to do so may be related to a breakdown in attention allocation strategy as considered below.

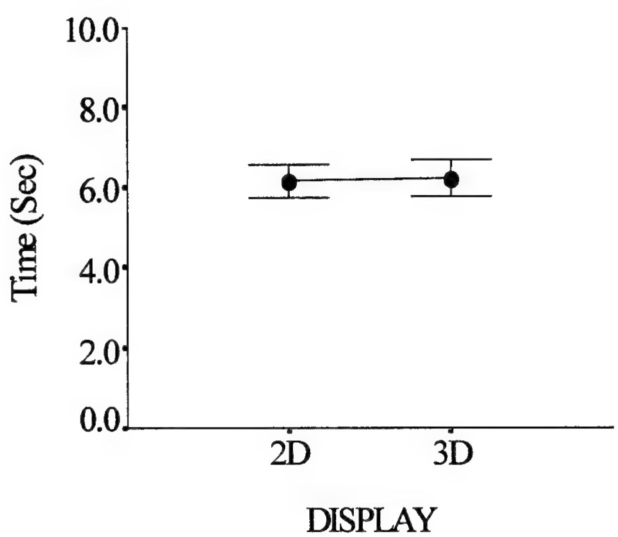
Therefore, although object displays did disambiguate the 3D exocentric display when compared to Olmos' 3D display, they did not completely eliminate the problem of ambiguity in contrast with the 2D coplanar display or the SS display suites. Additionally, the 3D immersed display of the SS display suite showed costs regarding horizontal axis judgments caused by its ambiguous representation of distance along the line of sight.

Scanning Costs: When considering the remaining costs of the SS and coplanar displays in terms of scanning, recall that Olmos (1997) reported that the SS display suite showed a propensity for higher response latencies for events that occurred in the bottom, global awareness, panel due to the salience of, or the high level of engagement in, the immersed display. Our proposed solution to the problem was to employ flashing of the intruder as an attention guidance cue to draw the pilots' attention from the immersed display as described in section 1.6.4. Although, as discussed in section 4.3, flashing greatly reduced the affect of attention capture caused by the immersed display (See figure 4.4), the affect was not fully eliminated (See figure 3.7). Upon further analysis, it's apparent that the increased latencies depended on where in the SS display suite the intruder appeared. If intruders appeared in the local sector, and were therefore visible in the immersed display, the response latencies were lower than when intruders appeared in the global sector. This implies that despite the use of flashing, the scan cost to the SS display suite was not fully eliminated due to the propensity of the immersed display to capture attention.

However, the enhancements made to the 2D coplanar suite (the previously discussed use of VM.), in conjunction with the use of flashing as an attention cue, effectively eliminated any

scan cost remaining in that display format. The conclusion is supported by the IFF response latencies depicted in figure 3.7, showing the difference in RT between the non-integrated 2D display and the integrated 3D exocentric display. These results show that regardless of whether the pilots were looking at the HSD or VSD in the 2D coplanar suite or where the intruder appeared in the display, the IFF response latencies were equal to the response latencies of the integrated 3D exocentric display. Further support is provided by the equal vertical judgment response latencies between the non-integrated 2D and the integrated 3D display shown in figure 4.5. The equivalence of the former with the latter indicates that the VM manipulations eliminated the cost of scanning between the HSD and the VSD in the non-integrated display. It is important to explain why scanning (selective attention) costs were eliminated in the coplanar display but not in the SS display. In the coplanar display, all objects were represented redundantly in both displays. In the SS display, however, the only time objects were redundantly presented was when they were in the local sector.

Figure 4.5: Relative times to make vertical judgments using the current 2D coplanar display suite and the current 3D exocentric display.



Frame of Reference (Egocentric and Exocentric): At this point, consideration is given to the SS display suite and, in particular, to its unique combination of an egocentric display with an exocentric display as described in section 1.7.3. It is clear from the results of this experiment that an immersed, or egocentric, display format is superior to an exocentric

format for local guidance, hence replicating the findings of others (Barfield, Rosenberg, Han, and Furness, 1992; Haskell and Wickens,1993; McCormick and Wickens 1995; Olmos, 1997; Wickens and Prevett, 1995). The reason for the egocentric display's superiority is the "natural" or "out-the-window" presentation of information required by pilots to navigate and which mimics the view that pilots' are used to seeing. However, this benefit is offset by the lower support an immersed display gives to global awareness as a result of its restricted field of view (FOV), or "keyhole" effect (McCormick and Wickens, 1995; Olmos, 1997; Woods, 1984). The cost of the limited FOV was, in this study, partially eliminated by the use of the second display depicting information regarding the space outside of the FOV, as presented in previous sections of this discussion. Overall, the immersed display of SS display suite showed a strong benefit for local guidance but a marked cost for scanning caused by attention capture, which contributed to some of the SS display suite's global SA costs.

4.5 Conclusions

The goal of this study was to explore the effectiveness of enhancing 3D exocentric, 2D coplanar, and a split screen display to increase their support for guidance and spatial awareness in a low level flight environment. The general conclusion regarding the overall performance of the displays for local guidance and local and global spatial awareness is that the 3D exocentric display, even after its enhancement, did not support either local or global tasks as well as either of the other two display formats. There was, however, a cost - benefit tradeoff between the remaining two formats. The SS display suite shows a definite benefit for local guidance tasks which is balanced by relatively poor global awareness support for event detection and vertical axis judgments compared to the 2D coplanar suite. Therefore, a conclusion regarding which of these two display formats provides the best overall support for both local and global tasks must take into account the tasks performed and frequency with which they are performed. In a tactical low level flight environment, the local awareness and guidance tasks are continuous in terms of mission demands whereas global SA tasks are more likely to be intermittent. We conclude that the SS display suite is most likely the best candidate for use, given our experimental paradigm, since it provided the best support for the continuous task of local awareness and guidance and poor support for some, but not all, of the global SA tasks. The only drawback to this conclusion is the noted decrement of the SS display format to afford

experimental paradigm, since it provided the best support for the continuous task of local awareness and guidance and poor support for some, but not all, of the global SA tasks. The only drawback to this conclusion is the noted decrement of the SS display format to afford detection of events in the global sector. This study raised some questions regarding object displays and their use in a perspective or parallel projected 3D exocentric display which should be examined in future studies. Also, future research might examine different methods to eliminate the propensity of the SS display suite's immersed view to hold attention and find a method to provide precise information in the global view. Finally, the effectiveness of these types of displays should be explored for use in the unmanned aerial vehicle and remotely piloted vehicle domains.

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